Exploiting soil and terrain heterogeneity: An investigation into vigour and physiology of grapevines on and off ‘heuweltjies’ in the Western Cape, South Africa

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DECLARATION

By submitting this thesis/dissertation electronically, I declare that the entirety of the work contained therein is my own, original work, and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

ABSTRACT

The topic of landscape heterogeneity has captured the imagination of ecologists and agriculturists alike and has been extensively investigated in this dissertation. Heuweltjies are landscape features putatively created by the termite *Microhodotermes viator* through their burrowing and nest-building activities. They have been closely examined in the natural veld of the Western Cape in the recent past and are the focus of many ecological studies. However, the effect of heuweltjies in cultivated landscapes (e.g. vineyards, orchards and wheat lands) remains unexplored. This study contributes significantly to our understanding of soil modifications associated with heuweltjies, as well as the physiology of vines growing on and off heuweltjies and wine made from these vines. It was hypothesized that heuweltjies occurring in cultivated areas can significantly affect crop yield and quality, thereby establishing itself as a potentially important role player in the agricultural economy of the Western Cape. This study was conducted in two climatic regions of the Western Cape, Stellenbosch (Mediterranean climate, Cabernet Sauvignon) and Robertson (semi-arid climate, Shiraz) to better understand how differences in heuweltjie characteristics correspond to differences in rainfall and temperature. In both study areas, heuweltjie soils were compared to non-heuweltjie soils with respect to physical and chemical. Grapevines associated with these heuweltjies were also compared to those growing on the adjacent, non-heuweltjie soils to determine any variation in vine vigour, physiology, phenology, berry characteristics and wine quality. Through the use of ANOVA's and Fisher's LSD posthoc tests to indicate statistical significance in soil and grapevine characteristics, it was apparent that heuweltjies induce substantial changes in soil and vine properties. Significant differences in the water content exist between the soils of the heuweltjies and non-heuweltjie areas. Heuweltjie soils exhibited higher values in comparison to the non-heuweltjie soils in the Stellenbosch study area, with opposite results in Robertson. Heuweltjie soils also displayed higher exchangeable calcium and magnesium and higher total carbon and total nitrogen values than non-heuweltjie soils in both study areas. Differences in physiology were more subtle, but vine vigour was severely altered on the heuweltjie-associated vines, exhibiting excessive vegetative growth in Stellenbosch, leading to variations in berry characteristics on and off the heuweltjies. Again, the opposite was observed for Robertson. Lower sugar and alcohol percentages and higher titratable as well as malic acid concentrations were observed in the wines emanating from the heuweltjies in Stellenbosch. Sensory analyses proved significant, as lower astringency and alcohol burn were detected in the Cabernet Sauvignon heuweltjie wines than the non-heuweltjie wines in the Stellenbosch study area. Chemical differences in the wines from the Robertson study are were insignificant. However, a significantly lower fruitiness was observed in the Shiraz heuweltjie-wines when compared to the non-heuweltjie wines. Differences in soil water content between heuweltjies and its adjacent soils was the most influential factor in this study, and affected all of the soil-grapevine interactions to a large extent. Further research need to be conducted to better understand and clarify the reasons behind these variations, as well as possible effects of global warming on heuweltjie functioning in different climatic regions of the Western Cape.

OPSOMMING

Die onderwerp van landskap heterogeniteit het die verbeelding van beide ekoloë en landboukundiges aangegryp en is op `n omvangryke wyse ondersoek in hierdie tesis. Heuweltjies is landskap eienskappe geskep deur die uitgrawe en nesbou aktiwiteite van die termiet *Microhodotermes viator*. Heuweltjies in die natuurlike veld is intensief bestudeer in die onlangse verlede en is die fokus van `n verskeidenheid ekologiese studies. In bewerkte landskappe (bv. wingerde, vrugteboorde en koringlande) is daar egter `n groot tekort aan navorsing oor die invloed van heuweltjies. Hierdie studie dra grotendeels by tot ons begrip van heuweltjie-geassosieërde grondverandering, asook die fisiologie van wingerd wat groei op en af van heuweltjies, sowel as die wyn afkomstig van hierdie wingerdstokke. Hipoteties sal heuweltjies in bewerkte areas die gewasopbrengs asook –kwaliteit betekenisvol beïnvloed en word so dus gevestig as `n potensieël belangrike rolspeler in die landbou-ekonomie van die Wes-Kaap. Die studie was onderneem in twee klimaatstreke van die Wes-Kaap, Stellenbosch (Mediterreënse klimaat, Cabernet Sauvignon) en Robertson (semi-ariede klimaat, Shiraz) om vas te stel hoe verskille in heuweltjie eienskappe ooreenstem met verksille in reënval en temperatuur. In beide studie areas is heuweltjie gronde met nie-heuweltjie gronde vergelyk met betrekking tot fisiese en chemiese eienskappe. Wingerdstokke geassosieër met heuweltjies is ook vergelyk met dié wat heuweltjies omring om enige variasie in groeikrag, fisiologie, fenologie, druifkorrel eienskappe en wynkwaliteit te bepaal. Deur gebruik te maak van ANOVA's en Fisher se LSD posthoc toetse om statistiese betekenisvolheid in grond- en wingerdeienskappe aan te dui, was dit duidelik dat heuweltjies wesenlike veranderinge in dié eienskappe teweegbring. Betekenisvolle verskille heers in die waterinhoud tussen die heuweltjie en nie-heuweltjie gronde. Heuweltjie gronde het hoër waardes getoon in vergelyking met die nie-heuweltjie gronde in die Stellenbosch studie area, met teenoorgestelde bevindings in Robertson. Heuweltjie gronde het ook `n hoër konsentrasie uitruilbare kalsium en magenesium, en totale koolstof en stikstof in vergelyking met nie-heuweltjie gronde. Verskille in fisiologie was baie meer subtiel, maar wingerd groeikrag was beduidend verskillend op die heuweltjie-geasossieërde wingerdstokke, met oormatige vegetatiewe groei in Stellenbosch wat lei tot `n verskil in druifkorrel eienskappe op en af van die heuweltjie. Weereens is die teenoorgestelde waargeneem in Robertson. Laer suiker en alkohol persentasies, asook hoër titreerbare - en appelsuur konsentrasies was te bespeur in die wyne afkomstig van die heuweltjies in Stellenbosch. Sensoriese analise het betekenisvolle verskille bewys, met `n laer vrankheid en alkohol-brand sensasie waargeneem vir die Cabernet Sauvignon heuweltjie wyne as die nie-heuweltjie wyne in die Stellenbosch studie area. Chemiese verskille in die wyne vanaf Robertson was onbeduidend. Sensoriese analise het egter anders bewys, met `n betekenisvolle laer vrugtigheid te bespeur in die nie-heuweltjie wyne as die heuweltjie wyne in die Robertson studie area. Verskille in die grondwaterinhoud tussen heuweltjies en omringende gronde was die mees invloedryke faktor in hierdie studie en beïnvloed tot `n groot mate al die grond-wingerdstok interaksies. Verdere navorsing is nodig om helderheid te verskaf agter die redes vir hierdie variasies, sowel as moontlike gevolge van aardverwarming op funksionering van heuweltjies in verskillende klimaatstreke van die Wes-Kaap.

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I can do all things through Christ who strengthens me

- Phillipians 4:13

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CHAPTER 1 –INTRODUCTION

1.1 General

The first governor of the Cape, Jan van Riebeeck, was very eager to establish viticulture in the Cape. He ordered vine cuttings from Europe and planted the very first vineyard in South Africa in the Company's Garden in 1655 which produced wine on 2 February 1659. Van Riebeeck's diary entry on that historic day speaks for itself: "Today, praise be to God, wine was made for the first time from Cape grapes …" (van Riebeeck, 1958). The aim of the VOC's ("Vereenigde Oost-Indische Compagnie") refreshment station instituted in the Cape in 1652 was simply to supply fresh products to the merchant fleet on their expeditions to the East. Little did they know that it was the start of an empire, a flourishing wine industry which later paved the way for the birth of a nation. However, it was only between 1680 and 1690, after the French Huguenots settled in the Cape, that the wine industry started to blossom. Their skills together with their rich wine culture and background left a lasting impression on the South African wine industry (Van Zyl, undated).

The total land area of the Western Cape extends over 129 370 00 ha, comprising of about 10.6% of South-Africa's total. One of the six recognized floral kingdoms, the Cape Floral Kingdom, can be found in the Western Cape. The main vegetation type of this kingdom is the indigenous Fynbos which is tremendously rich in species diversity and contains a bigger plant species variety on Table Mountain alone than the whole of the United Kingdom (Anonymous, 2007).

The Succulent Karoo vegetation type occurs in the more arid regions and makes up the majority of the remaining vegetation in the Western Cape. Dwarf, succulent shrubs dominate the vegetation with the approximately 16% of the world's 10 000 succulent species occurring in the Succulent Karoo Biome (Driver *et al.*, 2003), and thus it is safe to say that in an arid area of this size, the species diversity of especially the succulents is unmatched anywhere in the world.

Embedded in the diverse landscape of the Western Cape are microhabitats called 'heuweltjies' or little hills. Evidence suggests that these raised mounds of calcium-rich soil were created through nest-building and burrowing activities by the southern harvester termite *Microhodotermes viator* (Milton and Dean, 1990), and often support unique plant populations which vary considerably from the vegetation in the surrounding areas. These heuweltjies are distributed over mostly the western parts of South Africa, across gradients in altitude, rainfall, soil and vegetation type, with their northern and south-eastern boundary being the Orange River and Oudtshoorn respectively (Lovegrove and Siegfried, 1986). The area of their distribution corresponds with the geographical range of *M. viator*, fitting neatly into the Fynbos and Succulent Karoo Biomes (Coaton and Sheasby, 1974). There are, however, areas with *M. viator* activity where heuweltjies do not occur e.g. Nama Karoo and Namibia, with the reason being the interactive effect of the different soil physico-chemical properties and rainfall on mound structure and density (Lepage and Darlington, 2000).

The Tygerberg derived its name from the occurrence of heuweltjies on the hill, turning into yellow spots in the summer as the vegetation patches changes colour as it dies back, due to the decrease in rainfall and soil water content (F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication; Ellis, 2001). Rainfall and grazing pressure determine the type of plant communities associated with heuweltjies, whether annuals, grasses or thicket elements, which ensure that heuweltjies are floristically varied (Knight *et al.*, 1989).

Heuweltjies in the Succulent Karoo Biome comprise of a central calcrete or dorbank hardpan, with the outer edges consisting of petrocalcic or petroduric horizons, and are absent on base poor parent material e.g. sandstone (Ellis, 2001). According to Rebelo *et al.* (2006), animals like aardvarks (*Orycteropus afer*), porcupines (*Hystrix africaeaustralis*) and bat-eared foxes (*Otocyon megalotis*), as well as herbivores, often use heuweltjies for burrows and resting places. This influences the dynamics of the community considerably.

It is apparent that the majority of the Western Cape's total land area is utilized for agriculture, which according to the Provincial Spatial Development (2005) is 79%. Of this percentage, viticulture is practiced only over relatively small areas in comparison to other fields of agriculture. At the end of 2009, 348 608 447 grapevines were already planted in the Western Cape of which 303 799 724 were wine grapes. In the Western Cape, this constituted a land use of approximately 125 002 ha under grapevine cultivation, which accounted for 9.64% of the total land use. The contribution of South Africa's wine industry to the annual national Gross Domestic Product (GDP) was estimated at R 26.2 billion at the end of 2008, which represents 2.2% of the total GDP. However, only R14.2 billion remained in the Western Cape. South Africa is also the ninth largest producer of wine in the world (South African Wine Industry Information and Systems, 2010).

Between the eighteenth and nineteenth, the wine industry expanded greatly and much of the Western Cape's indigenous vegetation were converted to vineyards. It was speculated that the once thriving animal populations, like the noble termites, would have been largely destroyed due to cultivation and tillage of the soil. However visual investigation of satellite imagery and aerial photographs clearly suggest that the effect of heuweltjies on plant vigour, physiology and phenology is still visible in cultivated landscapes (Dean and Milton 1999, Krug and Krug, 2007). This is clearly depicted in Figure 1.1.

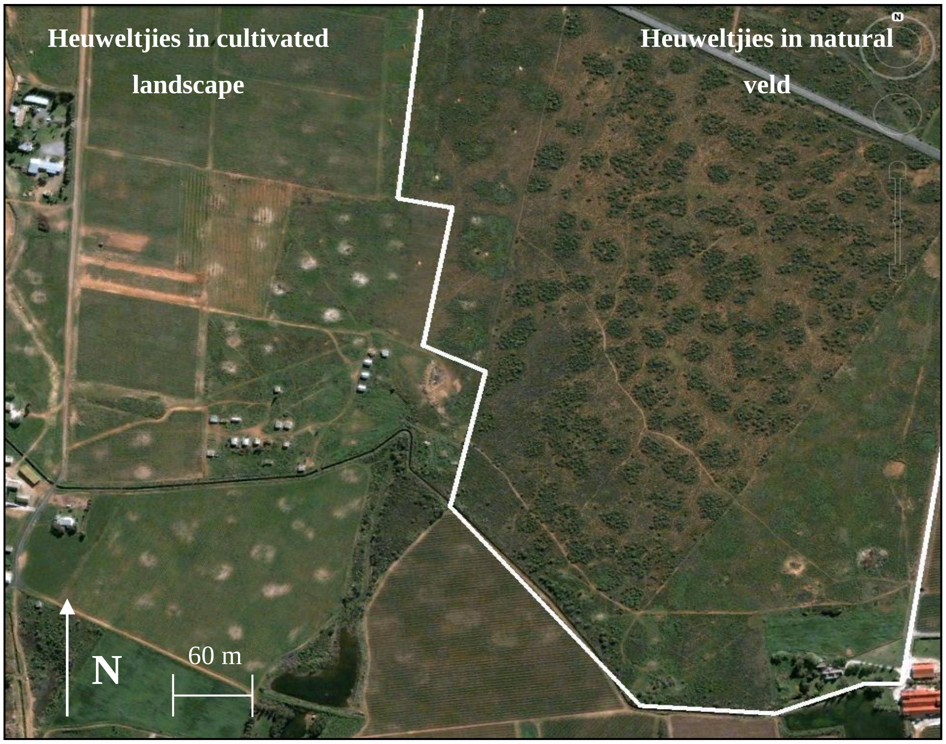

Figure 1.1: An aerial photograph clearly portraying the occurrence of heuweltjies in a vineyard in the Robertson area, as well as the contrast to the heuweltjies in the natural veld (Google Earth, 20 September 2010).

Shange *et al*. (2006) confirmed this hypothesis at a site in the Stellenbosch area. Their results indicated that heuweltjies under grapevine cultivation tends to retain some of the characteristics associated with those growing in natural Fynbos, e.g. supporting more vigorous grapevines. They also found that the increase in leaf density was to be to the detriment of wine quality as this leads to greater shading of the grape bunches, therefore delaying the time of ripening and influencing berry composition. In contrast with the more vigorous growth in Stellenbosch, it has been shown that the presence and persistence of heuweltjies in drier areas can inhibit the growth of the grapevines associated with the heuweltjies and thus leads to less vigorous growth (A. Strever, Senior lecturer Viticulture, U.S., 2010, personal communication).

Over the last couple of years much emphasis has been put on the concept of terroir. The diversity of the vineyards in the Western Cape, as well as the wines emanating from the subsequent different wine producing areas are vast, therefore terroir became a integral role player in the management of viticultural practices. Terroir is primarily composed out of climate, geology, soil and topography (Laville, 1993) out of which soil is considered to be one of the most influential factors. Manipulation and modification of this factor through intervention by soil biota, specifically termites, can shift the boundaries for the wine industry by generating biodiversity as well as expanding the options surrounding development of new vineyards.

1.2 Research objectives and overall aim of study

1. To determine the underlying basic soil properties of heuweltjies and to compare it to the adjacent non-heuweltjie plots at four sites in two areas (Stellenbosch and the Robertson valley).
2. Establishing reasons for differences in physical, chemical, biological properties on and off the heuweltjie.
3. To determine the vigour of the grapevines growing within each site on heuweltjies and adjacent non-heuweltjie areas in the two areas.
4. To determine physiological traits/properties of grapevines growing on the four sites in the two areas.
5. Determination of berry characteristics and wine chemical and sensory attributes from the vines on and off the heuweltjies.

The overall aim of this study was to determine what the effects are of the persistence of heuweltjies in cultivated landscapes in Mediterranean and semi-arid climates on soil characteristics, grapevine vigour and wine quality, and what advantages and disadvantages, if any, this will lend to agricultural activities.

1.3 Hypothesis

Based on the results of similar studies, both in natural veld and cultivated landscapes, we hypothesized that soil physical and chemical properties would vary considerably between heuweltjie and non-heuweltjie soils. We speculated that this might have significant influences on the grapevines associated with the heuweltjies, inducing variation in physiology, phenology, productivity, vine vigour, berry characteristics and ultimately wine quality between heuweltjie and non-heuweltjie vines.

1.4 Structure of dissertation

This dissertation comprises over two data chapters in the format of articles, preceded by a general introduction and literature review chapter. Repetition does occur due to some factors in the chapters displaying similarities, which therefore needed to be restated. The utmost was tried to keep the overlaps to a minimum.

Due to the wide range of interest in the heuweltjie concept and its effects on the growth of the grapevine, the funding organization of the South African wine industry (Winetech) has funded a research project with the aim to delve deeper into the science of heuweltjies and to explain the effect thereof on grapevines and ultimately on the wine quality. Therefore we have embarked on an extensive campaign of integrating and consolidating all areas and aspects of the soil properties, grapevine physiology and wine making associated with heuweltjies. This dissertation will contribute significantly to the investigation.

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CHAPTER 2 – LITERATURE REVIEW

1. Heuweltjies as a landscape feature

Heuweltjies are prominent landscape features in the South Western parts of South Africa. They occupy roughly 14-25% of the land surface (Picker *et al.*, 2006*;* Lovegrove and Siegfried, 1986, 1989), averaging 17 m in diameter and 1.45 m in height (Moore and Picker, 1991). Many theories have been postulated for their origin, ranging from soil movement by mole rats to geological models (Moore and Picker, 1991). Research conducted recently suggests that they are large and mature, long-lived mounds of the southern harvester termite *Microhodotermes viator* (Milton and Dean, 1990; Moore and Picker, 1991). Evidence for this is the contemporary presence of *M. viator* in a high percentage of heuweltjies and also the presence of fossil *M. viator* tunnels in the calcrete (Moore and Picker, 1991). These termite species is endemic to the Western Cape and occurs both in the winter - and summer-rainfall regions (Coaton and Sheasby, 1974). Bio-turbation by mammals like the mole-rat, *Cryptomys hottentotus*, cannot be excluded (Lovegrove and Siegfried, 1986).

Heuweltjies normally do not occur in mountainous areas whereas they flourish in inland valleys and the lowlands of the West coast (Lovegrove and Siegfried, 1986). The termites create nests underground and generate patches of disturbed soil which differs from the surrounding environment. However, it is primarily in, and on the fringes of the Karoo that *M. viator* builds surface mounds above their nests (Coaton and Sheasby, 1974), and where the majority of heuweltjies are found. Bio-turbation by mammals like the mole-rat, *Cryptomys hottentotus*, cannot be excluded (Lovegrove and Siegfried, 1986).

Due to the acute differences in soil properties between the Fynbos and Succulent Karoo Biomes, distinctions can be derived between the heuweltjies associated with the two Biomes, in reference to size, composition and distribution. In Fynbos and Renosterveld, heuweltjies are common, especially in the winter-rainfall regions and can range from 10 to 20 m in diameter and up to 5 m high (Rebelo *et al.*, 2006), with shale or granite layers usually just a few meters beneath the soil surface (Lovegrove and Siegfried, 1986; Knight *et al.*, 1989; F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication). The Succulent Karoo heuweltjies are approximately 30 m in diameter and 1 m high, and through comparison with the heuweltjies in the Fynbos, it is clear that there are significant differences in its dimensions.

1.1 Origin of heuweltjies

There are basically two hypotheses regarding the origin of mounds occupied by *M. viator*. Research by Midgley *et al.* (2002) suggested that modern conditions are insufficient in explaining the distribution and density of the mounds. They obtained heuweltjie ages that fell within the Pleistocene (30 830 years ago). They also showed three factors that suggest these features did not originate as recently as first thought. First, the spatial congruence between the occurrence of heuweltjies and the present termite (*M. viator*) is poor. *M. viator* also occurs in many areas within the fynbos biome where heuweltjies are absent. Also, *M. viator* hives occur off heuweltjies as well as on heuweltjies, in areas in which heuweltjies do occur (Burgers, 1975; Swift, 1994). Secondly, *M. viator* does not construct large sandy mounds (Coaton and Sheasby, 1974; Ruelle, 1985) and thus it is not apparent how these heuweltjies of 20 m diameter was created, even over thousands of years. The third reason is that only rarely does *M. viator* make its nests above the surface (Coaton and Sheasby, 1974; Ruelle, 1985). The older ages of the heuweltjie origins, as suggested by Midgley *et al.* (2002), places them in a time when the Cape was possibly more open and grassy (Parkington *et al.*, 2000), as well as cooler and wetter and thus more temperate.

The second hypothesis demonstrates that there is a clear relationship between current rainfall patterns and termite mound dispersion (Picker *et al.*, 2006). Their research suggests that the mounds are a dynamic feature of the landscape and are not fossil nests of an extinct species of termite dating back more than 20 000 years, which is now colonized by *M. viator* (Midgley *et al.,* 2002). The great age of individual mounds, between 5215 years (Moore and Picker, 1991) and 30 380 years (Midgley *et al.*, 2002), as well as the correlation of the mound densities with current rainfall patterns, are indicative of a rather constant rainfall regime over the last few thousand years (Picker *et al.*, 2006). This view is in direct contrast to the research of Midgley *et al*. (2002), who suggest that 'heuweltjies are not in equilibrium with modern conditions', and were established before the last glacial maximum. A wetter climate and a greater proportion of grass in the western parts of *M. viator's* range as well as a drier climate in the eastern parts of the Fynbos biome during the Pleistocene were indicated by palynological studies (Picker *et al.*, 2006; Parkington *et al.*, 2000). These termites mainly forage on non-grass detritus, with a low proportion of grass being present within the termite's range. The significant correlation between mound densities and rainfall, as indicated by Picker *et al.* (2006), shows that the system probably developed under Holocene rainfall patterns in the Western and Northern Cape Provinces. This positive correlation is also likely to be influenced by global warming and changing weather patterns, which will have a negative effect on *M. viator* through the change in rainfall and changing vegetation communities (Picker *et al.,* 2006; Schlesinger *et al.,* 1990). The older ages suggested by Midgley *et al.* (2002) may have come through sampling the calcrete from fossil termitaria that were distinctly different from heuweltjies (Picker *et al.,* 2006).

1.2 Geographical distribution of heuweltjies

Heuweltjies seems to be restricted mainly to areas below the Great Escarpment - defined as the higher lying mountainous or escarpment that separates the higher lying inland from the lower lying coastal region (Ellis, 2001). This area is susceptible to regular fog that comes from the nearby cold Benguella current. Heuweltjies can also be found in diverse environments, ranging from Succulent Karoo, Coastal Renosterveld and Fynbos (Picker *et al.*, 2006). According to Ellis (2001), the soil in the central part of the heuweltjie is more base-rich, commonly calcareous, than in the outer non-calcareous parts or in between the heuweltjies. The heuweltjies are virtually absent on base-poor parent material, like sandstone. They also contain higher concentrations of nutrients than the soils surrounding the heuweltjies (Picker *et al.*, 2006; Midgley and Musil, 1989). On-mound soils are also more aerated with increased water availability as well as higher levels of both macro- and micro-elements. The infiltration and absorption rates on heuweltjies can be impaired and are related to formation of algal crusts or salinity (Palmer *et al.*, 1999). It is thus self-evident that on-mound vegetation is distinctly different from that occurring off-mound (Picker *et al.*, 2005; Knight, Rebelo *et al.*, 1989; Midgley and Musil, 1989). It is believed that the above mentioned factor of greater aeration and porosity will also aid in the infiltration of water in mound-soils, but further research is needed in this field to justify this statement.

Heuweltjies are generally capped with a sand layer (Picker *et al.*, 2006; Milton and Dean, 1990), a fact that is strongly supported by Ellis (2001) which stated that evidence of various stages of land degradation in the form of soil erosion was noticed on the heuweltjies. The soils and vegetation cover that generally occur on and between heuweltjies, differ significantly (Ellis, 2001). Heuweltjies in all stages of development can be distinguished, which range from loose soil and plant debris over young termite colonies, to large mounds up to 32 m in diameter (Lovegrove and Siegfried, 1989). The formation of heuweltjies is a slow process where mounds form above the nests, where after they increase in size (with the concomitant development of a drought-deciduous and halophytic plant community), and then contract once they have passed a certain stage, probably when they are no longer occupied by *M. viator* (Milton and Dean, 1990). Once the termite colony has died, leaching of nutrients gradually changes the vegetation type and composition and animal use of the heuweltjies tend to decrease (Yeaton and Esler, 1990; Milton and Dean, 1990).

1.3 Heuweltjie structure

Many studies have been undertaken to describe the actual structure of the heuweltjie which is illustrated in Figure 2.1. The majority of these studies were carried out in the arid and semi arid regions of the Western Cape, which include Clanwilliam, Piketberg, Vredendal and Robertson. In a study conducted in the Clanwilliam district by Moore and Picker (1991), it was found that the majority of the mounds had a central depression and displayed a certain degree of asymmetry, with the various layers accentuated down slope. They divided the mound macro-structure into three layers:

1. A restricted calcified and brecciated basal zone resting on sandstone bedrock. They found that the basal portions were usually concentrated on the upslope side and in the central depression. It was also highly calcified, compacted and in some places, brecciated. Trace-fossil tunnels occurred as casts due to the replacement of the mound rock.

2. A central zone of compacted red-brown sandy rock, which makes up the bulk of the heuweltjie, succeeded the calcretized part. This zone contained a distinct, abrupt stratification, particularly on the down slope side. The more lithified lower portions could be compared with areas of secondary silica cement and contained

calcified crusts, either as laminated surface rinds or as fissure fillings cutting across the layers of the mound.

3. A grey unconsolidated sandy upper layer, which they found to be filled with fine calcified cracks and calcrete casts of fossil tunnels preserved in the lower parts. The uppermost portions of the intact mounds consisted of fine, unconsolidated sand, actively reworked by a variety of mound inhabitants, such as termites (*M. viator*, *Amitermes* sp.), ants (*Crematogaster melanogaste, Camponotus fulvopilosus* and *Messor sp.*), burrowing bees (*Bathyergus suillus*) and aardvarks (*Orycteropus. afer*). A maze of tunnels and chambers constructed by the harvester termite *M. viator*, however, dominated the entire subsurface portion.

Similarly, they also divided the mound micro-structure into groups. Termite construction took four principal forms:

1. The most common constructions were the narrow, tubular tunnels of about 3 mm to 1cm in diameter that were continuous throughout the mounds. According to them, the densest concentration of these tubular tunnels occurred in the mound peripheries. This is also the area where the tunnels are best preserved.

2. They also found a second type of construction composed out of wide, straight tunnels with ellipsoidal cross-sections (>1cm), that extended radially from the central depression to the periphery of the mound.

3. The third type of construction found in the mound is the kidney shaped temporary storage chambers (5-6 x 3-4 cm) with a highly polished internal surface and large-diameter access tunnels. The storage chambers occurred in a calcified state.

4. The hive itself was the fourth structure which inhabited the termite nests and took the form of a assemblage of horizontal shelves constructed of compacted organic matter

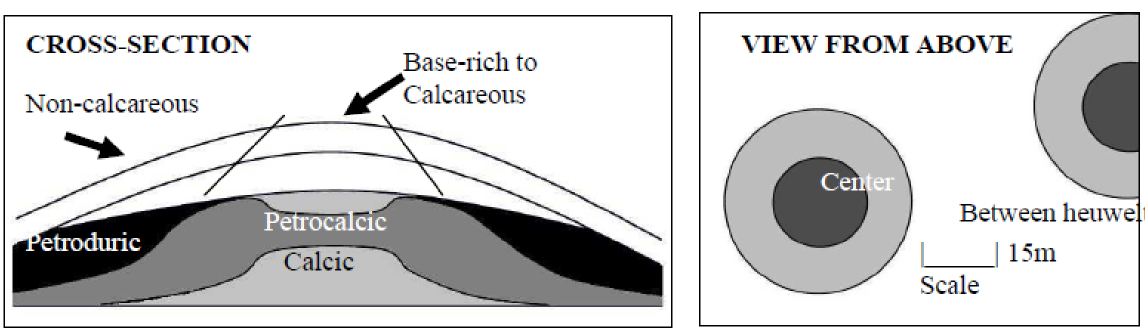

Figure 2.1: The horizons and material that is found on heuweltjies as well as the relative positions of the heuweltjies in the landscape (Ellis, 2002).

In the process of nest-building, subterranean termites burrow through the soil and create a series of tunnels and channels. The tunnels are used to obtain resources and protect their colony from predation and unpleasant environmental conditions (Tucker *et al.*, 2004). Their findings emphasized that tunneling is just another way of excavating soil particles by worker termites and that it is a process greatly influenced and in fact, limited by their mandible's ability to manipulate only specific particle sizes.

Termite constructions include numerous galleries in the soil: chambers housing the queen, king, larval nurseries and fungal gardens (especially in *Macrotermitinae* nests as shown in Figure 2.2) as well as soil sheeting covering the soil surface (Bignell and Holt, 2002). Mando (1996), found three types of burrows that occur in the mound structure. The first kind was subsurface tunnels resulting from the construction of sheeting; the second type was channels created by the termites as they left their nest while the third type was the product of nest construction. According to his findings, type one burrows are short-lived, but as long as the termites are present and active, they are constantly renewed and improved, thus contributing significantly to an increase in water infiltration. Type two and three burrows are persistent and can still be recognized even if the termite colony has left the nest. Although *M. viator* is a plant feeding termite, this section gives a general, but comprehensive description of the common termite's habits and immediate surroundings.

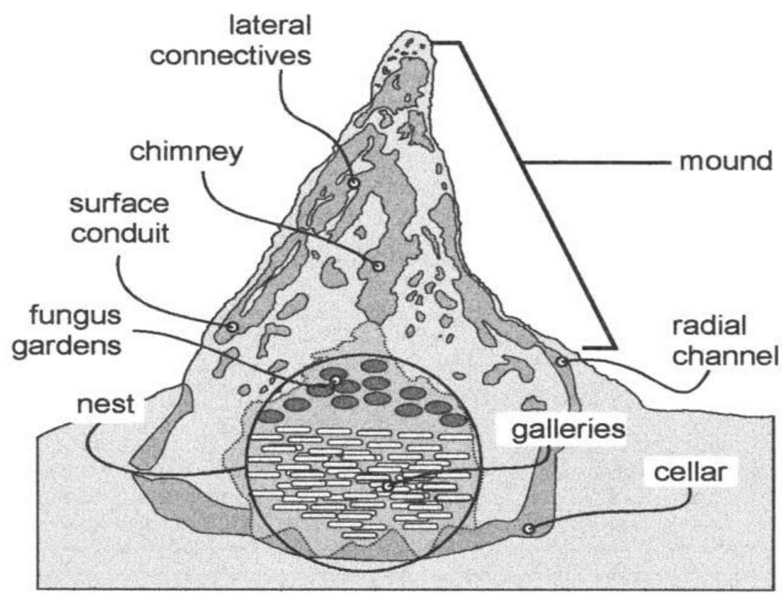

Figure 2.2: Cross section of the neat and mound of *Macrotermes michaelseni* (adapted from cross sections of a mound analyzed in northern Namibia (Turner, 2000).

Termite tunneling is more commonly described as excavation of individual soil particles by worker termites. Workers pick them up to carry and deposit them on the soil surface or in seldom-used tunnels as backfill. However, soil excavation is dependent on particle sizes that can be manipulated by a worker's mandibles; therefore, particle size is a limiting factor in some termite species' ability to tunnel. This will inevitably amount to some termite species preferring finer textured soils which will ultimately influence heuweltjie distribution. However, this limitation is not recognized for *M. viator*, which in general does not have a specific preference concerning soil texture.

1.4 Heuweltjie composition

1.4.1 Physical and chemical properties of heuweltjie associated soils

The mound itself is made up of sandy-to-silty mound rock and overlying unconsolidated soil, where the intermound areas are richer in gravel- and pebble-sized rock fragments (Moore and Picker, 1991; Merryweather, 1965; Burgers, 1975). In these heuweltjies, Cox *et al.* (1987) also observed an increase in the mass of pebbles towards the base of the mounds, however, they did not distinguish between 'concretionary' (i.e. calcified) and 'non-concretionary' (i.e. bedrock) fragments in their experiments. Thus the concentration of these pebbles towards the base of the mounds may partially be due to the process of calcretization (Moore and Picker, 1991). A finer size fraction dominates the termite mounds, in comparison with the adjacent areas in coarse soils, due to the limited particle size that can be transported by the worker termites (Moore and Picker, 1991; Lee and Wood, 1971b).

The occurrence of calcium carbonate in the basal portions of termite mounds are widely reported (Moore and Picker, 1991; Hesse, 1955; Lee and Wood, 1971b; Watson, 1974). Two processes have been proposed for this precipitation of calcium carbonates. The first model, developed by Hesse (1955), suggests that the evaporation of calcium bicarbonate-bearing groundwater as it rises by capillary action within the mound, would take a very long time (thousands of years) to precipitate significant amounts of calcium carbonate. Watson (1974) introduced the second model that requires saturation of the base of a termite mound, which has a higher soil pH, by calcium bicarbonate-bearing groundwater of lower pH. Equilibrium is therefore attained by the precipitation of calcium carbonate. If the groundwater flows temporarily through the base of the mound (for instance on a slope), the calcretization process can be quite rapid (Moore and Picker, 1991; Semeniuk and Meagher, 1981).

Turner (2001) investigated the factors influencing gas exchange in the mounds and nests of *Macrotermes michaelseni*. The results showed that gas exchange rates within the colony are mainly determined by complex interactions, linking the architecture of the mound and nest with the wind’s kinetic energy as well as with the naturally induced convection induced by termite metabolism. According to Turner (2001) this convection may participate in mechanisms which inspire homeostasis in the nest’s atmosphere.

According to Bignell and Holt (2002), the materials utilized, manufactured or transported by termites will include surface soil, subsurface soil, compacted faeces and carton, which is an organic-rich mixture of partially digested cellulose, saliva and soil.

Construction of the termite mounds has the result of mixing the soil with other materials e.g. feces, leaf litter, dry grass and decaying wood, thus changing the chemical and physical properties of the mounds. This occurs where the accumulation of these materials take place as well from surrounding areas where these materials are transported (Robert *et al.,* 2007; Lee and Wood, 1971b). During the time that termites occupy the soil, they will collect living plant tissue and organic debris that they transport to the mound, where after it will be extensively degraded by the termites (Robert *et al.,* 2007). Consequently organic matter and plant nutrients are excluded from the plant-soil cycle which again leads to a change in soil properties. This will have an effect on the productivity of the ecosystem and influence processes such as nutrient cycling, soil texture and carbon sequestration (Robert *et al.,* 2007).

1.4.1.1 Changes in physical properties

The activity of termites in the repacking of soil particles, augmented with organic matter emanating from saliva and faecal products during mound construction is imperative (Holt and Lepage, 2000). Subterranean chambers and galleries constructed during mound building are prominent in termite inhabited soils and can account for up to 2 % of the total soil volume in the profile, with effects on both infiltration rates and drainage (Bignell and Holt, 2002). Due to the redistribution of the soil and other materials in the mounds it is most likely that the subsequent change in texture will be associated with changes in physical properties like water holding capacity, infiltration rate, permeability, structural stability and bulk density (Robert *et al.,* 2007; Wood and Sand, 1978).

It seems that termites are very specific as well as consistent when it comes to the range of particle sizes they prefer to build their nests (Robert *et al.,* 2007; Lee and Wood, 1971b). In a study conducted by Kemp (1955), mounds of the species *Cubitermes* were shown to be composed of approximately 67.2% clay and 26.5% sand in comparison with the 30.8% clay and 63% sand found in the adjacent soils. In similar studies conducted in Western Africa, Watson (1962) found that the soils associated with the termite mounds contained about 94% fine material (clay and silt) in comparison to the 52% fine material in the surrounding soils. According to Jouquet *et al.* (2004), who studied the soil structural stability of termite nests (*Macrotermes bellicosus*), the percentage of clay will increase in the mound soil while at the same time sand and coarse silt content will decrease. This gives rise to an increase in the amount of cations as well as an increase in cation saturation exhibited in the material of the mounds. The increase in the number of cations would then also amount to a higher pH in the mound soils (Jouquet *et al.*, 2004).

In studies done by Pathak and Lehri (1959), mound soils were found to have a much greater water-holding capacity than the surrounding soils. The soils of the mounds had a water-holding capacity of about five times that of the adjacent soils. This was confirmed by Elkin and Sabadol (1986), and again by Jauen and Valentin (1987). It has also been stated that soils associated with termite mounds provide better drainage when compared to the surrounding soils (Arshad, 1982).

According to Jouquet *et al.,* (2004), the structural stability of the termite mound soil is governed by two factors:

i) The higher clay content in the termite mound leads to a decrease of pore sizes and consequently a slower rate of water diffusion.

ii) 2:1 clay types will swell with infiltration of the water into the soil, which in turn leads to a breakdown in the stability of the mound soil.

It is therefore obvious that clays play an integral role in stabilizing the structure of termite mounds (Jouquet *et al.*, 2004).

1.4.1.2 Changes in chemical properties

The difference in chemistry between the soils of the heuweltjies and intermound areas is significant, with enrichments in Ca, Mg, K, P, Mn and N (Moore and Picker, 1991; Midgley and Musil, 1990). This difference in composition supports the involvement of termites as similar results of these enhanced levels of Ca, Mg, K, P and N have been reported from a wide variety of termite mounds (Moore and Picker, 1991; Lee and Wood, 1971b; Pomeroy, 1983; Okello-Oloya *et al.,* 1985; Okwakol, 1987). The higher values of these specific elements are due to the elevated concentrations of clay particles and organic matter containing exchangeable cations in the termite mounds compared to the surrounding soils (Moore and Picker, 1991).

In studies by Lal (1988) and Brouwer *et al.,* (1991), they showed that the soils of the termite mounds can either have greater or reduced values of total nitrogen, organic carbon, exchangeable calcium, magnesium and potassium, available phosphorus and effective cation exchange capacity (CEC) when compared to adjacent soils. It has also been found that termites will influence processes such as organic matter decomposition, pedogenesis as well as nutrient cycling (Lavelle *et al.,* 1994; Robert *et al.,* 2007).

A higher organic carbon, C/N ratio, Ca, Mg, P, K concentration were found in the mounds of *Odontotermes* and *Macrotermes* species when it was compared with its surrounding soils in Nigeria (Ekundayo and Aghatise, 1997). According to studies conducted by Frageria and Baligar (2005) in an oxisol in Brazil, the activities of termites resulted in a significant increase of organic matter, exchangeable cations, micro-nutrients and the pH of the mound soils. Soil acidity in terms of Al also decreased in the mounds. Zech *et al.,* (1997) also stated that soil carbon stabilization is higher in the termite mounds than in the adjacent soils. This was demonstrated by the higher carbon content in the silt size seperates. Rawls *et al.* (2003) illustrated that the organic carbon content is an important property influencing the soil's water retention (Figure 2.3).

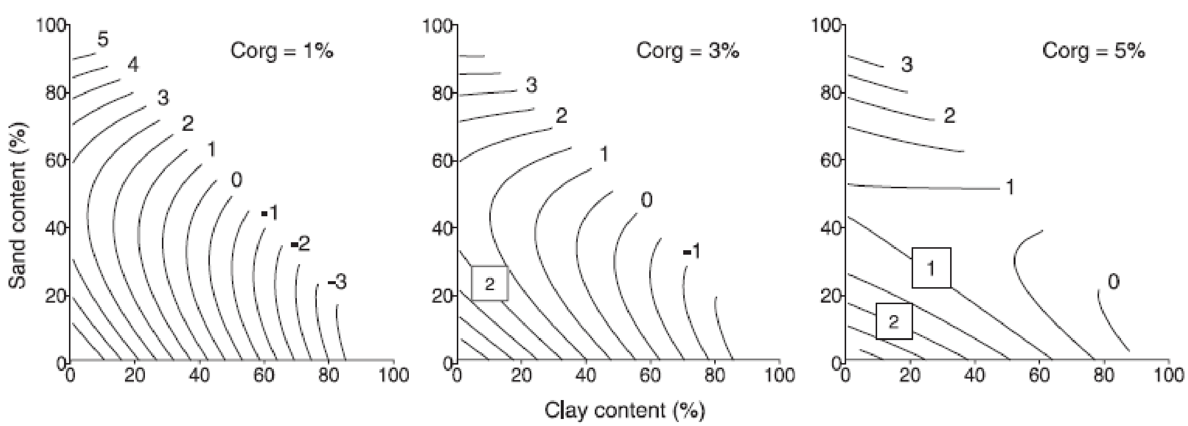

Figure 2.3: Changes in soil water content at -33 kPa (volume %) per 1% change in organic carbon content with various initial carbon contents C_{org} (Rawls et al., 2003).

Pearce (1997) reported increased levels of extractable Ca, Mg, Fe, Al N, Cr and Silica in the mounds of *Trinervitermes* and *Hodotermes.* He also concluded that the nests by *Odontotermes* species displayed higher contents of ferric and aluminum oxides, as well as higher concentrations $CaCO_3$ than the adjacent soils. On the other hand, mounds have also been associated with low organic carbon contents as Malaka (1996) stated. When he compared the mound soils to the surrounding soils he recorded a lower organic carbon content, but a higher Ca, Mg and K in *Macrotermes* mounds than in the surrounding soils. According to Jones (1973) and Cabrera (1993), the lowest carbon content and C/N ratio was found in the soils of *Macrotermes* and *Odontotermes* mounds (Robert *et al.,* 2007).

In a more recent study by Abe and Wakatsuki (2010), it was found that termites such as the *Macrotermes bellicosus* species can have a direct effect on the form and composition of free sesquioxides in the soil due to the accumulation of fine particles in their mounds. Added to this phenomenon could be the indirect effect of changes in soil redox conditions by the transportation of particles from reductive waterlogged subsoil to oxidative topsoil. The activity of termites in the soil, which includes epigeal nest-building, can therefore have a major part to play in the spatial distribution of free sesquioxides and can add considerably to soil mineralogical as well as ecosystem diversity.

1.5 Effect of heuweltjies in cultivated landscapes e.g. vineyards

All through the 18th and 19th century, large areas of natural veld that formerly sustained healthy and thriving harvester termite populations were converted to either cropland or vineyards (Dean and Milton, 1999; Krug and Krug, 2007). Due to intense cultivation and tillage of soil, it is palpable that animal communities would for the most part have been eradicated, but through visual investigation of aerial photographs it is clear that effects on plant vigour, physiology and phenology are still very much evident in these cultivated landscapes. Vegetative growth is also affected by the variation in soil and was verified by the study of Shange *et al.* (2006), which illustrated the differences in grapevine characteristics, observed in different climate zones. At a location in Stellenbosch, which falls under a Mediterranean climate, it was found that heuweltjies under grapevine cultivation retain some of the inherent characteristics associated with those growing in natural Fynbos, for example sustaining more vigorous grapevines. The greater density of the canopy induces a shading effect which especially influences the composition and distribution of the inner leaves and bunches. Reduced levels of grape chlorophyll, flavonols and anthocyanin as well as higher grape malic acid and K levels are normally the implications of the shading effect (Shange *et al.,* 2006; Downey *et al.,* 2004; Spayd *et al.,* 2002; Keller *et al.,* 1999; Smart and Robinson, 1991; Illand, 1989). The opposite was discerned in areas with a lower rainfall where grapevines associated with heuweltjies tend to be less vigorous (Shange, *et al.*, 2006).

According to the study of Shange *et al.* (2006) in Stellenbosch, the soils that occurred on the heuweltjies, displayed a darker top soil and brownish B horizon in comparison with the off-mound soils. This darkening of the soil can be attributed to the accumulation of organic material in the mound by termites. (Soil Classification Working Group, 1991). Shange *et al.* (2006) also indicated that active earthworms were present in the first and second horizons on the heuweltjies, most probably due to the favourable environment that the termites created (Dawes-Gromadzki, 2005). Signs of wetness were observed in both the heuweltjie and off-mound soils, although it was more visible in the second and third horizons of the off-mound soils than the heuweltjie soils (Shange *et al.*, 2006). They also found the heuweltjie soils to have a non-uniform colour which could probably be attributed to the presence of clay cutans and channel fillings with earthworm casts, as well as turbation previously caused by termites (Dawez-Gromadzki, 2005).

Shange *et al* (2006) also stated that the heuweltjie soils had a higher bulk density than the soils that occurred in-between the heuweltjies. This phenomenon could be due to the reworking capabilities of the termites. As the termites rework the soil they excrete soil materials, thus filling the micro-pores with their faeces. An increase in volumetric water content of the heuweltjie soils can be linked to the increase in soil volume and bulk density (Dawez-Gromadzki, 2005). They also hypothesized that earthworm activity may have a stabilizing effect on micro aggregates which are rich in organic C and fine material particles (Pulleman *et al.*, 2005). The visibility and occurrence of clay illuviation was also much clearer in the off-mound soils than in the heuweltjie soils. This again could have been attributed to faunal turbation (Shange *et al.*, 2006; Dawez-Gromadzki, 2005). The levels of Ca in the heuweltjie soils also increased in comparison with the off-mound soils (Shange *et al.*, 2006).

In a study about the nutrient dynamics in termite mounds of *Nasutitermes ephratae* in Venezuela, by López-Hernández (2001), it was concluded that the mounds contained more C, N and P than adjacent topsoils due to the use of faecal material to line their gallery walls, as well as the use of sand particles with the faecal matter as cement, in construction of their termitaria (López-Hernández, 2001; San José *et al.*, 1989).

2. Effect of climate, topography and soil properties on the growth and physiology of the grapevine as well as on wine quality

The main objective of modern viticulture is to maximize fruit quality in the vineyard. For optimal fruit quality, the grapevines need to be "balanced". A balanced grapevine is one that produces economically sufficient yields with enough vegetative growth to ripen the fruit (Wheeler and Pickering, 2003). Environmental factors play a major part in the success of a vine, both in terms of yield and fruit quality. The factors that will be considered here include those of climate, topography and soil, as well as their respective subcategories. The concept of terroir will lead the introduction to a more in-depth study of above mentioned factors.

2.1 Terroir concept

According to Laville (1993), a natural terroir unit (NTU) is a unit of the earth's surface, characterized by fairly homogeneous trends in topography, climate, geology and soil. A NTU has an agronomic potential that is displayed by the uniqueness of its products, giving rise to the terroir concept. Therefore, a terroir can be better defined as an integration of natural environmental factors difficult to adjust by the producer, and cannot be viewed separate from management and cultivation practices (Carey *et al.*, 2001).

Viticultural terroirs are identified and described according to the above mentioned definition. According to Seguin (1986), a good terroir is one that guarantees complete maturation of the grapes with certain promptness with respect to wine quality from year to year. With an increase in the use of precision viticulture techniques, vineyards are divided into smaller sub-blocks that share similar attributes (NTU's) so that vineyard interventions can be applied exactly where required (Goode, 2003).

The study of NTU's is important for various reasons which according to Carey *et al.*, (2001), are fivefold:

1. Recognition of viticultural terroirs is of international importance and the *Office International de la Vigne et du Vin (OIV)* has passed a resolution requiring that all wine producing countries submit terroir characterization (Anon, 1993).
2. The terroir concept emphasizes the fact that winemaking already commences in the vineyard and although the final wine character and style are influenced by numerous factors, an unwavering set of environmental features establishes the basis of the viticultural ecosystem.
3. There seems to be an emerging interest in the origin of wines, and the demarcation of NTU's in association to viticulture plays a vital role regarding consumer demands.
4. The terroir concept should include the demarcation of areas of origin and therefore terroir studies create and provide a scientific basis to this system.
5. Terroir studies will help producers better understand their own vineyards, and subsequently improve the quality of their products.

Carey (2001) also illustrates the influence of specific aspects of terroir which have a major effect on the growth of the grapevine (Figure 2.4). This clearly depicts that terroir is a central and significant factor that can directly as well as indirectly manipulate wine quality.

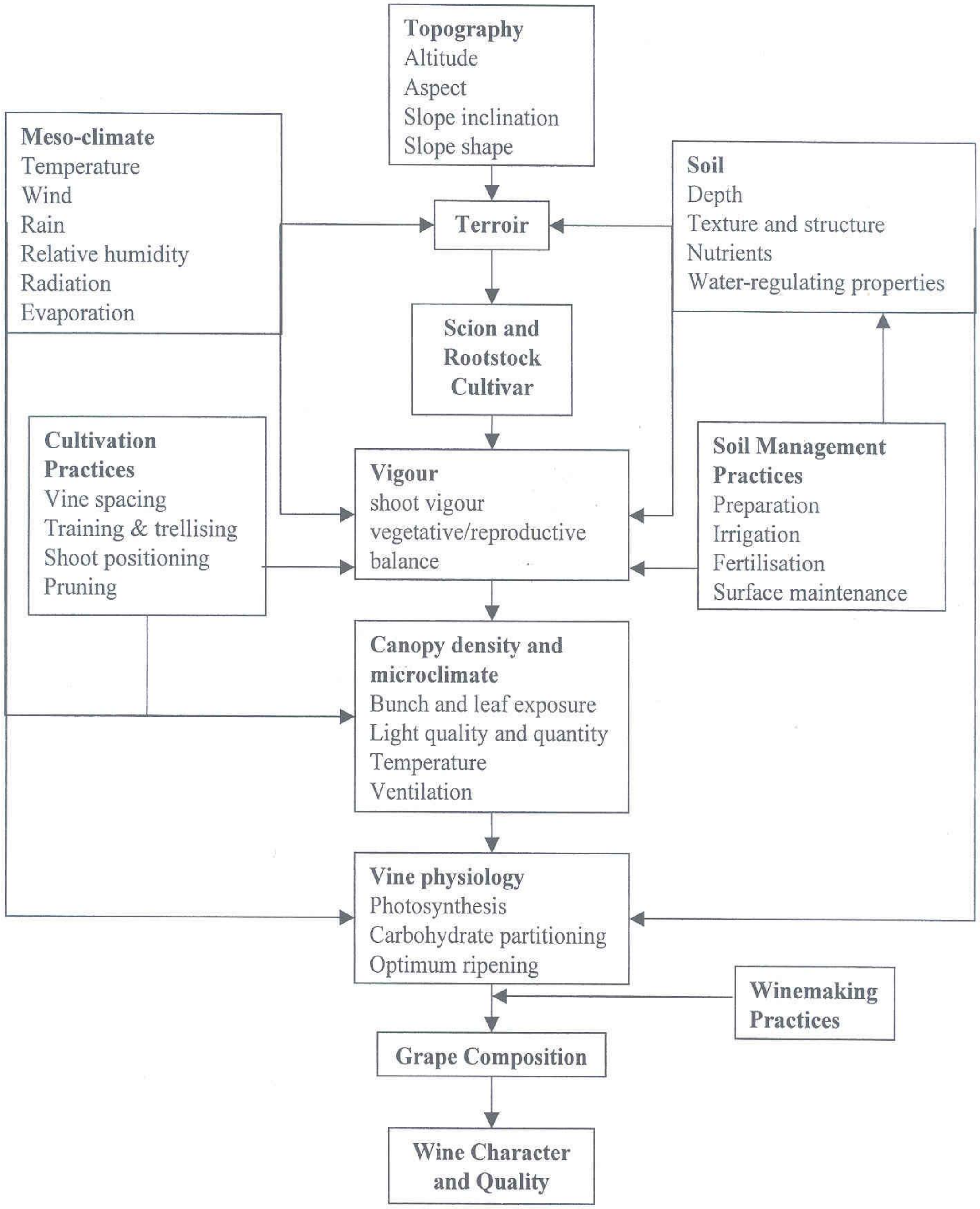

Figure 0.4: Interaction between environmental and management factors that influence grape composition, wine character and quality (Carey, 2001).

2.2 Climate

2.2.1 Temperature

According to Coombe (1987), temperature is probably one of the most significant factors affecting the grapevine as it affects most aspects of the growth and functioning of the vine. High temperatures have a very significant effect on the grapes, up to a certain temperature threshold. Sugar content will be slightly higher while grapes lose malic acid at greater rates as mean temperatures at ripening are higher (Gladstone, 1992). Potassium content will also increase, thus affecting the wine pH (Carey, 2001).

Bunches need a constant input of sugar to produce grapes that will give high quality wine (Gladstones, 1992). This is only accomplished by the grapevine if conditions are optimum for photosynthesis. Aroma, flavour and colour are all dependant on enzyme activity which in turn depends on the photosynthetic products. High temperatures can interrupt processes and can lead to a deceleration of ripening. An average mean temperature below 15ºC causes grapes to reach ripeness with high acid levels. In experiments conducted by Gladstones (1992), he concluded that a more narrow range of variation about a given mean ripening temperature will produce greater grape flavour, aroma and pigmentation at any given time in ripening and sugar level. He found that mean temperature to be between 20 and 22ºC.

According to Kliewer and Torres (1972), the day temperature and the temperature variability will have a significant influence on the effect that night temperatures have on anthocyanin synthesis. When the daily thermal amplitude was greater than 10ºC, they found that fruit colouration was greatly reduced. However Jackson and Lombard (1993) found that low night temperatures are necessary for lower pH values and higher natural acidity when day temperatures are warm. Studies show that extremely high temperature (>38°C), persisting for more than six hours a day, will reduce anthocyanins in the skin of the berry, increase in berry desiccation, poor berry colour and flavour, and low quality juice. Photosynthesis might be severely impaired, with stomata closing at these temperatures (Jones *et al.*, 2005).

2.2.2 Rainfall and humidity

The availability of water at specific growth stages of the grapevine has important and complex implications. According to Van zyl and van Huysteen (1984) and Ludvigsen (1987), heavy spring rains may affect setting and fruitful bud differentiation through vigorous vegetative growth. On the other hand they found that the vines will tolerate water stress well from bud differentiation to just before véraison. From véraison to harvest it is essential that there is continuously enough water to keep the vines healthy and to nurture the crop to full maturity. Rain during ripening can, on the other hand, be harmful as it can cause serious berry splitting. Adequate, continuous water supply from harvest to normal leaf-fall will lead to complete maturation of the vine as well as a good build-up of assimilate reserves (Gladstones, 1992).

A high rainfall or excessive irrigation normally leads to vigorous growth and has a negative effect on the quality of the grapes. It can also induce the formation of actively growing shoots in the latter stages of ripening, thus influencing the accumulation of reserves in the bunches. A high pH and low acid content is normally associated with these conditions (Roux, 2005).

One of the important factors causing water stress in arid climates is the vapour pressure saturation deficit, which is determined by the relative humidity and temperature. Very high relative humidities can promote fungal diseases, especially when the temperatures are high (Gladstones, 1992). Relative humidity also affect the rate of photosynthesis when there is a limited soil water supply. The maximum rate of photosynthesis will occur when the relative humidity is between 60 and 70%. (Champagnol, 1984). Hot, atmospherically dry climates will cause an increase in the natural must and wine pH as well as reducing the growth and yield per unit water transpired. The relationship of pH to atmospheric saturation deficit is probably one of the reasons why most of the world's best table wines come from areas that have a fairly high daytime relative humidity.

2.2.3 Wind

Wind can have both positive and negative effects on the growth of the grapevine. One of the positive effects includes the maintenance of air circulation and prevention of excessive humidity build-up within the vine canopy. It is also helpful in preventing frosts during the cold winter nights. The movement of the leaves due to wind allows the intermittent illumination of internal leaves by beams of sunlight which then increases the photosynthetic efficiency (Gladstones, 1992).

Another positive influence of wind is the effect of a cool sea breeze, which can be defined as "a local wind occurring during the afternoon as a result of differential heating above the land and the sea" (Bonnardot, 1997). The sea breeze has an effect on the relative humidity as well as the diurnal temperature variation. The sea breezes reduces the vapour pressure deficit, lowers the maximum temperature and slows the decrease in evening temperature which again results in a longer period during the day that is optimal for photosynthesis and physiological ripening (Gladstones, 1992).

According to Gladstones, strong winds are almost always harmful and wind damage can occur when strong winds in spring and early summer injures the shoots and bunches up to and including the time of setting (Hamilton, 1988). In an experiment done by Kobringer *et al.* (1984), grapevines that were subjected to winds of 3 – 4 $m.s^{-1}$ for three weeks showed reduced shoot lengths, leaf sizes and stomatal densities compared to those that were not subjected to wind. Freeman *et al.* in Kobringer *et al.* (1984) showed that Chardonnay grapevines exposed to 4 – 6 $m.s^{-1}$ winds had significantly lower stomatal conductance than the vines sheltered by a Eucalyptus windbreak, which reduced the windspeed to 1.5 $m.s^{-1}$.

2.3 Topography

One of the main factors affecting the quality of grapes and wine is the effect topography has on temperature variability (Gladstones, 1992). This author also hypothesized that there is a link between topography and suitability of soil type for viticulture. The effects of topography on climate can be indirect, due to factors like soil drainage, exposure to wind and ventilation or it can have a direct effect because of the change in the incidence of the sun's rays on the surface of the earth (Crowe, 1971).

Topography has a major influence on the movement and availability of water and therefore is a decisive factor during site selection for a vineyard. Air drainage is another important factor related to topography. Cold air is heavy and accumulates on concave slopes and in valleys (Figure 2.5). Trees and other vegetation and barriers can also obstruct the flow of cold air (Pool, undated).

Figure 2.5: A photograph that illustrates how cold air flows to the lower parts of a field, resulting in fog forming in the low areas. The cold air stays within the boundaries of the field due to the vegetation barrier (Pool, undated).

2.3.1 Altitude

A decrease in temperature takes place with increasing elevation and in South Africa, that decrease will be approximately 0.3ºC for every 100m above sea level (Le Roux, 1974). The amount of temperature decrease with increasing elevation will be less when there is a higher relative humidity, warmer soil surface, increase in radiation and poor ventilation (Gladstones, 1992).

In studies done by Jones (2007) on the effect of high altitudes on viticulture, he discussed the importance of climatic factors and the differences that can be associated with higher elevation vineyard sites. He concluded that elevated climates can be characterized by a combination of temperature, radiation, wind and rainfall patterns, and also by larger climate variability over spatial and temporal scales, compared with lowlands at the same latitude. He also said that while the growing seasons are shorter at higher altitudes, plant growth can be intense and vigorous due to the favourable radiation climate and the big difference between daytime and nighttime temperatures.

According to Gladstones (1992), grapes produced at high altitudes will result in a much higher ratio of potassium accumulation to sugar production in the leaves as well as a higher must pH. Grapes grown at higher altitudes can also develop a more favourable phenolic profile with increased levels of tannins and anthocyanins, as well as a more rounded tannin structure due to the lower levels of monomeric tannins. With all of these advantages, potential challenges associated with high elevation viticulture must also be considered. These include the increased risk of frost; extreme weather conditions such as heavy rains, hail, and strong winds that can damage the crop; higher costs for development and management of vineyard; soil erosion; uneven soil types and inconsistent soil fertility; variable grape maturation rates from bottom to top of slope; and lower overall yields (Smart, 1987).

2.3.2 Aspect

The aspect of the slope is regarded as an important factor regarding viticulture as it influences the mesoclimate through the amount of sunlight it receives and exposure to wind and rain (Schultz, 1997). The soils of east, north and west-facing slopes in the Southern Hemisphere, and of east, south and west-facing slopes in the Northern Hemisphere receive the most direct sunlight which results in higher soil temperatures and also a greater re-radiation of warmth to the grapevine in the early morning and at night, or under cloud cover. This effect is most significant at high latitudes, around budburst in spring and ripening in autumn (Gladstones, 1992). According to Schultz (1997), more radiation occur on northerly aspects as slopes become steeper, but less on southerly aspects in the Southern Hemisphere.

Aspect also influences the effect of prevailing winds and sea breezes and windward facing slopes can force moist air to rise which can result in higher frequency and quantity of rainfall (Schultz, 1997).

2.3.3 Significance of nearby water bodies

The average diurnal temperature range and the variability of the maximum and minimum temperature from day to day are greatly reduced when a vineyard is situated close to the sea. Inland rivers and lakes can have the same effect, because of the fact that surrounding land temperatures heats up to higher temperatures by day and cools off to lower temperatures by night, thus creating alternating cycles of air convection (Gladstones, 1992). Frost is also greatly reduced in vineyards within close proximity of the sea.

2.4 Soil

According to Saayman and Kleynhans (1978), the type of soil has a indirect effect on the wine quality, generally through the soil-water relationship and growth of the grapevine. While the soil water content is important, the more delicate attributes of grapes and wine may also be affected by the soil mineral characteristics (Champagnol, 1984).

Rankine *et al.* (1971) also came to the conclusion that the soil only has an effect on the concentration of some of the components in grapes and wine, but will not necessarily influence the wine quality. Seguin (1986) stated that areas consistently producing wines of premium quality generally contain soils exhibiting high permeability, good aeration and a good overall structure which will mitigate the effects of harsh conditions such as waterlogging or severe drought. During dry summers, the soils with the greatest water holding capacity produced wines with the highest aroma intensity, while the opposite was true for cooler and wetter summers (Conradie, 1998).

2.4.1 Soil physical properties

2.4.1.1 Soil colour

The colour of the soil is determined by the parent material from which it is derived as well as the forces that governed the soil forming process. Soil colour is of great importance due to the fact that it influences the air temperature closest to the soil as well as the soil temperature itself; certain soil characteristics are associated with a specific soil colour and the quality and colour of the reflected light influences the physiology of the leaves (Carey, 2001).

Under high rainfall conditions, a red colour indicates good draining, while soils with darker colours will indicate poor draining. Light coloured soils can be an indication of low amounts of organic material and also excessively fast leaching and draining as well as low soil potential and nutrient deficiencies (Saayman, 1981a). The colour of the topsoil may indicate the prevailing soil water conditions, while the colour of the subsoil is a good indication of the draining and aeration status of the soil profile. The presence of iron and aluminum oxides often create the colour of the subsoil.

An experiment on artificially coloured soils, controlled for other factors, was conducted by a few researchers and was explained by Fregoni (1977). He said that on darker soils there will be more vegetative growth, but a smaller yield due to berry splitting. He also explained that the length of the vegetative cycle varies with soil colour and that white soils will induce the most prolonged vegetative cycle (Roux, 2005). Darker soils will absorb more sunlight than light coloured soils which reflects the radiation of sunlight (Fregoni, 1977). Sauvage *et al.* (2000) conducted artificial solarisation experiments and concluded that the quality and quantity of the reflected light has a significant effect on the relationship between the sugar concentration of the grapes and its colour.

Heuweltjie soils in the more arid regions will contain a higher concentration of free lime than non-heuweltjie soils, resulting in a lighter colour and higher albedo. A higher percentage of the sun’s rays will be reflected by the soil, causing a lower soil temperature. It will also result in a higher reflection of radiation into the vine canopy and if temperatures and solar radiation become too intense, berries will be damaged.

2.4.1.2 Soil temperature

Soil thermal properties that include thermal conductivity, heat capacity and thermal diffusivity are required in a range of industrial, meteorological and agricultural applications (Lipiec *et al.*, 2007; Côtè *et al.*, 2005; Tavman, 1996). These properties play a big part in the partitioning of surface-energy and the resulting temperature distribution and moisture flow, and will thus form the microclimate for the soil and near ground atmosphere for plant growth and grape quality (Lipiec *et al.*, 2007; De Vries, 1987; Horton and Chung, 1991; Heilman *et al.*, 1996).

According to Carey (2001), soil is a function of the colour, texture and humidity of the soil. Fregoni (1977) stated that temperature is one of the main factors in the soil that governs root growth and absorption. Thus, growth resulting from favourable temperature conditions is more important for the nutrition of the plant and wine quality than growth resulting from a high concentration of nutrients in the soil. Woodham and Alexander (1966) also showed, by using a hydroponic system, that the growth and development of grapevines will greatly vary depending on the temperature in the rhizosphere. In an experiment by Skene and Kerridge (1967), they also found that the roots that formed at 30°C were longer and thinner in diameter than the roots formed at 20°C. On the other hand, Van Zyl and Van Huysteen (1979) suggested that the storage of carbohydrates in roots will be hindered by high soil temperatures. Soil temperature has a significant effect on the structural utilization of carbohydrate reserves from roots during the growth of the grapevine from anthesis to budbreak. It also has a strong positive relationship to shoot biomass and leaf area (Field *et al.*, 2009).

The water holding capacities of the heuweltjie soils may be significantly altered through manipulation by termites, incorporating clay and faeces into their nest for structural stability. In cultivated landscapes, research in the Stellenbosch area, with a Mediterranean climate shows that heuweltjie soils retain more water when compared to surrounding soils (Shange *et al.*, 2006). This factor combined with the higher concentration of free lime in the soil explained in the previous section, will inevitably lead to a lower soil temperature on the heuweltjies, in turn influencing vines in the manner described above.

2.4.1.3 Soil depth

Effective soil depth is defined as the depth of soil material that plant roots can penetrate readily to obtain water and nutrients (van der Watt and van Rooyen, 1995), and is determined by physical restrictions in the subsoil, whether it is an impermeable layer, water table or an abrupt change in the texture, as well as chemical restrictions like pH, salinity and sodicity. The effective depth of the soil can be considered as a buffer against adverse conditions such as drought and heat waves (Sequin, 1986). A vast range of soil depths can be used to grow grapes. In general a rooting depth of minimum 500 mm, preferably 800 mm is desired for grapevine cultivation. The size of the grapevine as well as their capacity to endure stress in the form of drought will be severely restricted (Pool, undated). A greater soil depth can increase the soil's water reservoir which is replenished by the winter rain and/or irrigation, and therefore support the grapevine for longer periods during the dry growing season (Roux, 2005). Soils with a greater effective depth also allows more consistent vine growth and distribution due to the cooler and more regular temperature range (Seguin, 1986).

Increasing the effective soil depth for grapevine cultivation proved beneficial in the past. The use of raised beds on top of the subsoil in a Chardonnay vineyard, improved the soil's physical and hydraulic properties because of the greater depth of the surface soil. That again led to optimized root and shoot growth of the vine (Eastham *et al*, 1996) In another experiment, the vegetative growth and yield of two-year-old Chenin blanc on 99 Richter rootstock on raised beds under microsprinkler irrigation, significantly increased in comparison with those grown on flat, unripped soils (Myburgh, 1994). Effective management of the raised beds, surface covers and irrigation can help to sustain soil physical fertility (Wheaton *et al.*, 2008).

The effective soil depth might be reduced in heuweltjies, especially in arid regions due to the accumulation of bases, low degree of leaching and subsequent formation of hardpans underneath the surface. This will inhibit root growth, distribution and penetration leading to limited water uptake by the vegetation associated with the heuweltjie.

2.4.1.4 Soil texture and structure

Soil texture must be considered when a rootstock is chosen due to its influence on vine growth and tolerance of nematode and/or phylloxera damage (texture affects the movement of the nematodes and phylloxera). Coarse-textured soils are much more conducive for nematodes while phylloxera is better adapted for finer-textured soils (McKenry and Christensen, 1998). As the soils associated with heuweltjies are more finely-textured than corresponding non-heuweltjie soils, through the incorporation of clay particles into their nest by termites, it makes for a much more attractive habitat for phylloxera. The texture of the soil will also influence the growth of the vine through its effect on the soil's water holding capacity and availability of nutrients.

Soil structure refers to the natural aggregation of soil particles to form aggregates which is split through points of weakness. The structure of the soil has a significant effect on the movement of water and nutrients through the soil as well on the growth and penetration of roots. In a study by Henry (1993), it was found that grapevine roots could not occupy pore spaces with a diameter of less than 200 µm. Soils that have a strong structure (eg. prismacutanic, lithocutanic or a hard plinthic character), will impede root growth and could cause a decrease in water and nutrient movement. Aeration will also become a problem unless artificial underground draining systems are installed. This will eventually be detrimental to the plant, as illustrated by Figure 2.6. Soils that are more friable will increase the movement of water and nutrients as well as the capacity of the roots to penetrate the soil through the increase in porosity and aeration (Roux, 2005).

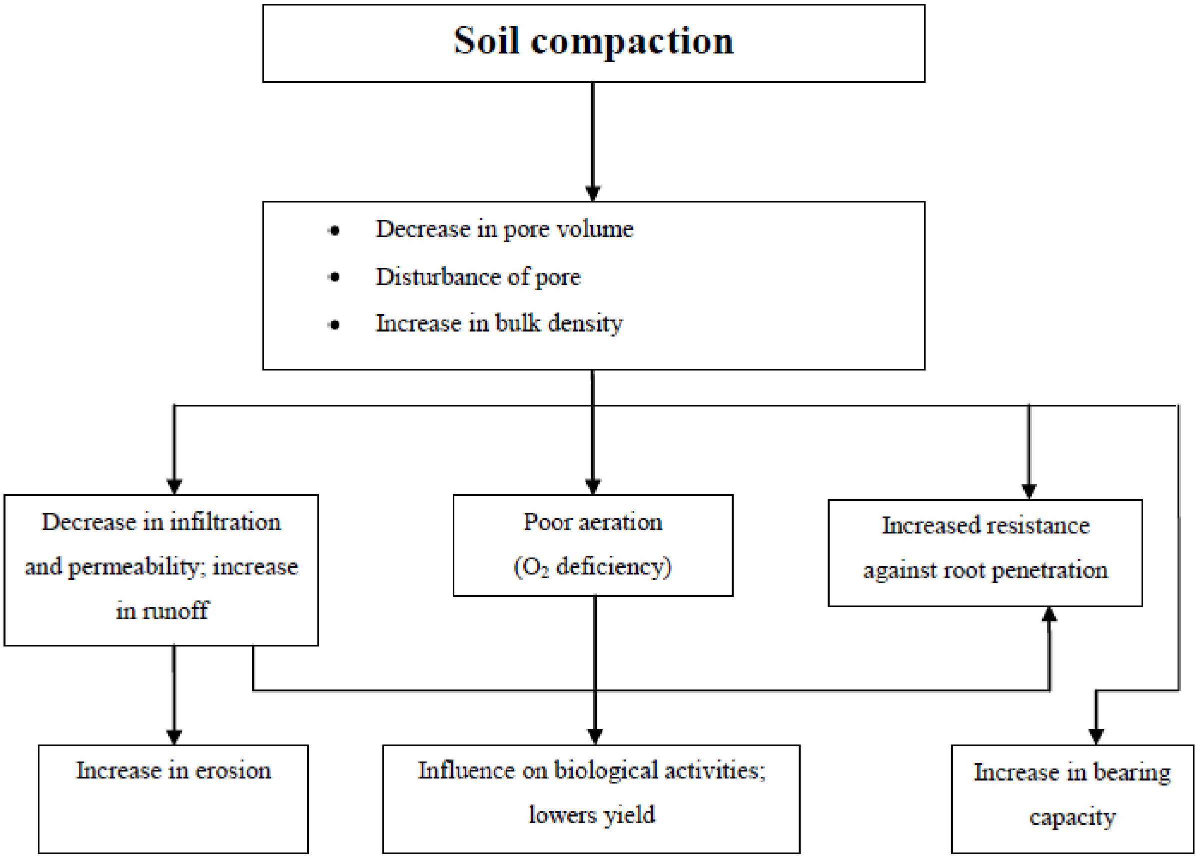

Figure 2.6: Effect of bulk density on soil properties (Du Toit, 2008).

Soils that contain a high percentage of stones and sand have a higher thermal conductivity than soils with a finer texture. That leads to coarse textured soils heating up much faster than finer textured soils, which in turn can have a positive effect on the root growth and uptake (Fregoni, 1977). These factors can have a positive influence on wine quality in the cooler Northern Hemisphere, but the opposite might be true in the warmer wine producing countries. The higher temperatures can cause a degradation of acids, aroma components and poliphenols in the grapes which leads to a decrease in wine quality (Carey, 2001).

2.4.1.5 Soil water status

The availability of water in the soil is the result of the actual amount of water present in the soil as well as the force of water retention that the soil exhibits (Champagnol, 1984). According to Carey (2001), soil depth, texture and structure will have an effect on the water-holding capacity of the soil as well as the available water for the vine. The soil's texture plays a significant part in water retention and influences porosity and pore-size distribution, as illustrated by Lambers (1998) in Table 2.1.

Table 2.1: Typical pore-size distribution and soil water contents of different soil types (Lambers, 1998).

Parameter	Soil type		
	Sand	Loam	Clay
Pore space (% of total)			
>30 µm	75	18	6
0.2-30 µm	22	48	40
<0.2 µm	3	34	53
Water content (% of volume)			
Field capacity	10	20	40
Permanent wilting point	5	10	20

The availability of water in vineyards can have a significant influence on the wine quality (Saayman, 1992a). Saayman and Kleynhans (1978) found that a water table at a certain depth can influence the growth, vigour and grape composition the same way as irrigation. Higher vine vigour, better overshadowing, delayed ripening and in general a higher acid content in the grape is the result. In a study by Conradie (1998) on Sauvignon blanc, he found that the aroma profiles of the wines from the same locality, but different soils, varied considerably. This effect was dependant on the season and was closely related to the soil water status.

In temperate areas where the rainfall is high, the soil needs to provide good internal drainage (Saayman, 1992b). Soils that are characterized by blue or white horizon colours are usually badly drained and must be avoided, while well drained soils (red to yellow colours) are preferred for dry land conditions. These characteristics, together with a good water-holding capacity and the absence of root impeding layers, are preferred for dry land conditions.

In a study conducted by Constantini *et al.* (1996) in Italy, it was found that high available water contents in a humid year will cause excessively fertile conditions in the soil as well as poor colour and phenolics in the berries. On the other hand they concluded that very low available water contents in hot and dry years will inhibit the accumulation of sugar and colour as well as hinder the grapevine's performance regarding the acidity of the grapes. According to them, the best enological results in a rainy year was achieved with an average soil water availability (from veraison to harvest) of approximately 3% by volume, while in drier years the optimum soil water availability was about 1%. These results show how difficult it is to exemplify optimum soil water content, as it varies every year according to weather conditions.

Previous research on natural heuweltjies' water characteristics in Mediterranean areas is meager. Experiments conducted in a cultivated land (vineyard) yielded results exhibiting higher volumetric water contents on heuweltjies when compared to non-heuweltjie soils in the Stellenbosch area (Shange *et al.*, 2006). This can be attributed to the increase in clay content, as termites incorporate clay into their mound during nest-building. However, results obtained in cultivated landscapes can significantly differ to heuweltjies in the natural veld, due to alteration of the micro-topography as well as soil properties by ploughing and soil tillage. Microtopographical as well as topsoil characteristics can be the cause of a drier moisture regime on the heuweltjie when compared to the surrounding soils, through the induction of water runoff (Prinsloo, 2005).

2.4.2 Soil chemical properties

The most important chemical property of the soil is its capacity to provide a steady, balanced nutrition for growth and development of the grapevine (Gladstones, 1992).

2.4.2.1 pH

Soil can be divided into three classes according to their pH, namely acid soils with a pH (KCl) of lower than 5.5; neutral soils with a pH (KCl) of 5.5 to 7.5 and alkaline soils with a pH (KCl) higher than 7.5. Soil pH can also have an effect on its cation exchange capacity (CEC). In low pH soils, the CEC is low and H^+ is dominant, while micro elements like aluminum, manganese and copper becomes available to the grapevine in toxic amounts. On the other hand, a high soil pH results in a higher CEC and the presence of calcium and sodium causes the vine to be subjected to salinity damage (Roux, 2005).

Conradie (1988) stated that approximately 70% of the vines in the Western Cape are grown on slightly acid soils, with a pH (KCl) below 5.0. He founded that root development is restricted in acidic soils. This may be a response of the grapevine to an unfavourable physical structure as well as aluminum toxicity. Symptoms like boron deficiency, reduced vigour, low productivity and low soil calcium and magnesium were also observed in areas like the Douro valley (Portugal) where grapevines were cultivated on acidic soils (Coutinho *et al.*, 2001).

In general, heuweltjie soils will exhibit a higher pH due to the accumulation of nutrients and bases in the mound by the termites (Ellis, 2001). The scale of variation in pH between heuweltjie and non-heuweltjie soils is generally dependant on the climate, soil type and in turn the degree of leaching endured by the soils.

2.4.2.2. Electrical Conductivity

Extreme soluble salt can accumulate in the soil due to climatic factors, occurrence of salt-rich rock, drainage pattern of the soil or surrounding landscape, poor water quality and incorrect management practices (Saayman, 1981b). The functioning of plants growing on these soils can be affected by the high osmotic pressure as well as by the high concentration of ions such as Na and Cl, that may be detrimental to the plant (Chapman, 1968).

Maas (1990) defined grapevines' sensitivity to salinity as moderate. According to Shannon and Grieve (1999) there are non-specific and specific mechanisms through which salinity have an effect on plants. The non-specific effect causes a decrease in the soil solution's osmotic potential that hinders transpiration and photosynthesis. The specific effects are linked to ion uptake as well as changes in the plant's physiological processes due to element toxicity and deficiency, or alteration in the mineral balance of the soil.

These results were also found in experiments with grapevines growing in saline soils. Walker *et al.*, (1981) reported stomatal closure which led to a decrease in photosynthesis and shoot growth. In relation to soil salinity, Downton (1985) and Fisirakis *et al.*, (2001) documented Na and Cl toxicity as they tend to accumulate in grapevines grown in highly saline soils. Differences in the Na:K ratio and resulting antagonism due to salinity have been reported by Downton (1985). In studies of Sultana vines, the same author again found a correlation between biomass production and transpiration. He also correlated the decrease in photosynthesis with stomatal closure and ensuing restriction of CO_2 into the leaves, under specific salinity levels. Saayman (1981b) indicates the estimated effect of high salinity in soils on grapevines in Table 2.2.

Table 2.2: Coherence between electrical resistance (R_s) of the saturated paste of a soil and the salinity and conductivity (ECe) of the saturated paste extract, as well as the estimated salinity effect on the grapevine (Adapted from Saayman, 1981b).

R_s (ohms)	Salt content of soil extract (%)	ECe (mS/m)	Effect on grapevine
1100	0.032	50	Effect of salinity insignificant
620	0.064	100	
350	0.128	200	
250	0.19	300	Symptoms of saline damage
200	0.26	400	
165	0.32	500	Serious saline damage; shoots not fully ripened
143	0.38	600	
126	0.45	700	
113	0.51	800	
102	0.58	900	Longterm viticuture not possible
94	0.64	1000	
87	0.7	1100	
81	0.77	1200	
76	0.83	1300	
71	0.9	1400	
67	0.96	1500	
64	1.02	1600	

2.4.2.3 Nutrients

In comparison with other horticultural crops, grapevines experience fewer problems with mineral deficiencies and fertilizer demands (Hirschfelt, 1998). Grapevines need a continuous, adequate supply of nutrients to sustain balanced and healthy growth and fruiting. A close relationship exists between a vine's susceptibility to diseases and the nutrient content of the soil (Grant, 2002), and a deficiency of especially nitrogen can be detrimental (Singh, 2006). Vines that are subjected to nutrient deficiencies tend to contract diseases more easily, whether fungal or bacterial. Soil organic matter (SOM) acts as a kind of reservoir of nutrients which is slowly released to plants through oxidation. It plays a big part in maintaining a friable, absorptive and erosion-resistant physical structure which in turn leads to a stronger water holding capacity. SOM originally emanates from decomposed plant material and its composition is very much the same as the requirements needed for initial plant growth (Gladstones, 1992).

Positive correlations have been found between the lack of sufficient nutrients in the soil and the quality of the wine obtained from that soil. According to Jackson and Lombard (1993), a high nutritional status together with adequate water and temperature, will have an indirect negative effect on the quality of wine as it affects the phenolic and aromatic compounds in the grape. This is due to higher vigour and pH. The cation exchange capacity (CEC) of plant roots is very similar to that of soil, therefore resulting in competition with each other for cations based on physicochemical principles (Rengel and Robinson, 1989).

Nutrient dynamics of heuweltjies has been a topic of discussion for numerous years now, whereby researchers attempt to clarify the accumulation of specific nutrients in heuweltjie soils in comparison with non-heuweltjie soils. As already stated, heuweltjie soils are augmented with Ca, Mg, K, P, Mn, N and organic C, as well as exhibit a higher C/N ratio than corresponding non-heuweltjie soils, both due to the transport of food (e.g. leaves and twigs) into the nest by termite and a higher CEC.

2.4.2.3.1 Nitrogen

A high supply of nitrogen can cause vigorous vegetative growth that may reduce yield and quality, especially if the correct trellising system is not used (Gladstones, 1992). It also stimulates the vine's metabolism which then metabolizes carbohydrates for vegetative growth, thus having a negative effect on sugar accumulation (Saayman, 1992a). According to Bavaresco (1989), excess nitrogen also increases the vine's susceptibility to diseases. It can also cause deficiencies of other elements through the increase of the growth, as well as by complexing the elements into inactive from within the vine. There is, on the other hand, no evidence that a deficiency of nitrogen is beneficial to the quality of the wine. Responses to nitrogen seem unlikely to affect wine quality given that proper and correct trellising systems are used to accommodate the growth (Gladstones, 1992).

2.4.2.3.2 Phosphorous

Plants take up phosphorous in the inorganic, orthophosphate (PO_4^{3-}) form (Hagen and Hopkins, 1955). The optimum P content is dependant of soil texture and varies with the clay content, as illustrated by Table 2.3. Phosphorous uptake can be significantly hampered when soil water content reaches wilting point (McMullen, 1995). Due to the fact that ligand exchange and precipitation reactions dominate in acidic soils, a low pH makes PO_4^{3-} unavailable to plants (Bache, 1964) and a P deficiency will start to develop in the plant. If this problem persists, it inhibits the initiation and maintenance of cluster primordia and will have negative effects on the fruit yield of grapevines (Skinner *et al.*, 1988). Vines with a P deficiency will also reduce leaf area which causes a decline in the photosynthetic capacity of the plant. Inhibition of shoot growth and petiole leaf concentration are also associated with P deficient vines (Grant and Matthews, 1996).

Table 2.3: Norms for the P content for different soil texture classes (Van Schoor *et al.*, 2000).

Clay %	Texture Class	P content (mg/kg)
0 - 6	Sand	20
6 - 15	Loam	25
> 15	Clay	30

2.4.2.3.3 Potassium

High potassium content in the soil is undesirable in arid climates, as it can have a potential negative effect on the pH of the must and wine, as well as on the colour of red wines (Jackson and Lombard, 1993). The subsequent greater potassium uptake per unit of vine growth and yield will cause the differences in soil to be more strongly reflected in the vine and the fruit (Gladstones, 1992). In these climates, the high potassium availability can cause unfavourable canopy light relations with irrigation which leads to the danger that too much potassium will be mobilized from the leaves to the fruit (Gladstones, 1992). There is much less of a risk of this in cool and humid climates and potassium deficiencies has been known to occur, which causes reduced growth and yield, as well as increased susceptibility to a number of fungal and bacterial diseases (Gladstones, 1992; Huber and Arny, 1985; Bavaresco, 1989).

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CHAPTER 3 – SOIL CHARACTERISTICS OF HEUWELTJIES

1. INTRODUCTION

The unique geography of the Western Cape together with the high variation in weather and periods of inundation by the ocean gave rise to considerable soil diversity over short distances. It is home to one of the world's six floral kingdoms, Fynbos, and whilst it is the smallest of the six, it is considered to be the most rich and bio-diverse. This bold, but true statement often initiate a serious of questions with the most obvious being: "what lies beneath?"

The landscape of the Western Cape consists of great heterogeneity, both on a spatial and temporal scale. This heavily influences the distribution patterns of plant and animal species and gives us an idea of productivity levels. The extensive biodiversity associated with the Western Cape protects human health and safety, provides us with economic benefits and offers us recreational and aesthetic enjoyment (Davis and Wynberg, 1998).

Predominantly two biomes prevail here, i.e. Fynbos and Succulent Karoo, which plays home to a large variety of soils (Figure 3.1). Upon examiniation of this figure, it is clear that soils differ considerably between the two study areas, Stellenbosch and Robertson. Stellenbosch soils are predominantly strongly structured, exhibiting a reddish colour and high clay content. Soils in Robertson on the other hand are mostly shallow on hard and weathered rock, with lime being present in most of the landscape. The Fynbos Biome comprise of a very large variety of soil types as a result of a wide range of environmental conditions, such as the age of landscapes, parent material, terrain type as well as past and present rainfall patterns. Various combinations of environmental conditions can construct different sequences of soil types and catenas (Lambrechts, 1983, Lambrechts and Fry, 1988). Low nutrient levels are common in the soils of the Fynbos Biome, which leads to plants exhibiting a low potential for seed dispersal. This can explain the high quantity of endemism observed here (Goldblatt, 1997).

The Succulent Karoo Biome borders the Fynbos Biome with which it shares its greatest floristic affinity to the east and the south (Hilton-Taylor, 1987). Due to its low average rainfall, special modifications are needed by the soil to ensure that plants can extract maximum water and nutrients more efficiently. Therefore the soils of the Succulent Karoo possess unique properties that enable it to adjust water infiltration, hydraulic conductivity, water-holding capacity and the supply of water to the plants (Mucina *et al.*, 2006). The soils are primarily derived from granite and gneiss, displaying a reddish colour, and are generally base-rich to calcareous, exhibiting a hardpan (dorbank). The soils of the Succulent Karoo are well supplied of nutrients, due to the low degree of leaching (Ellis, 1988). According to Whitford and Kay (1999), biopedturbation plays an extensive part in establishing heterogeneity with the impact on ecosystems being far greater in arid environments than mesic environments. Careful study and management is therefore needed to sustain the heterogeneity and preserve it for future generations.

It is in these two Biomes that termites create mounds through burrowing and nest-building activities, locally known as ‘heuweltjies’, which are major contributors to biodiversity and functional heterogeneity. Research shows that the contributory species fundamental in the formation of these heuweltjies, are *Microhodotermes viator* (Milton and Dean, 1990; Rahlao *et al.,* 2007). There is a very strong relationship between climatological data and the factors influencing pedogenesis and due to the fact that *Microhodotermes viator* is a climate-dependant organism, they only prosper in very specific environmental conditions and habitats.

Termites have been rightly given the title of soil builders and ecosystem engineers (Dangerfield *et al.*, 1998), and may have a vast impact on the life conditions of other species. They play a major role in establishing soil heterogeneity and by constructing physical structures in the soil, play a big part in inducing restructuration of their environment. This may result in proficient regulation of soil processes, specifically through changes in soils structure and organic matter dynamics (Decaëns *et al.*, 2001).

Some of termites’ traits include the changing of local infiltration rates and creating landscape mosaics; their impacts tend to increase because of the biophysical processes that occur in the soil. Their abundance and impact on soil properties varies greatly according to land use and vegetation, and continuous cultivation and soil tillage cause alteration in the population structure, reduction and even elimination of key termite species (Dangerfield, 1993). The processing of considerable amounts of material in their building activities, affects the soil properties in comparison to the adjacent soils (Lee and Wood, 1971b; Lobry de Bruyn and Cornacher, 1990).

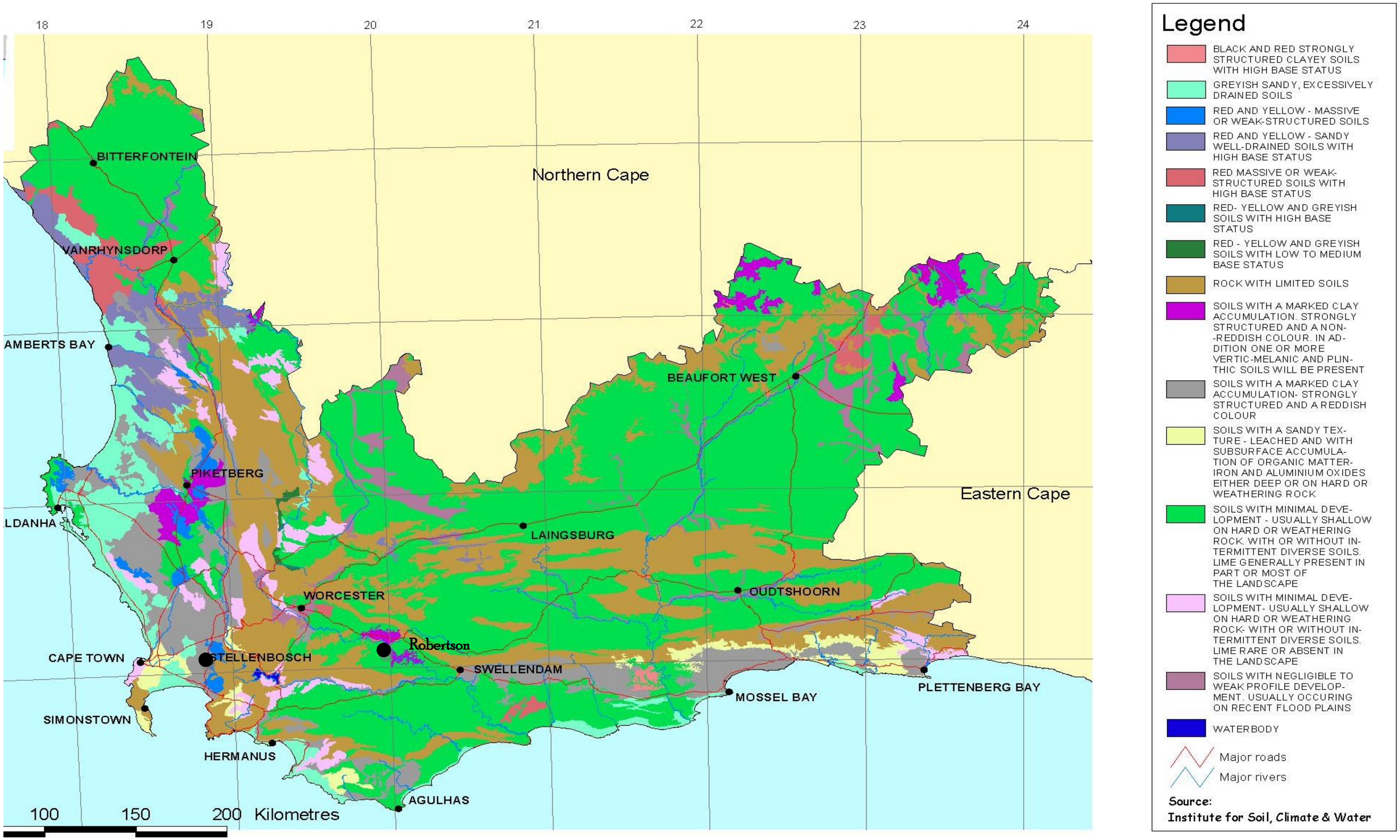


Figure 3.1: Distribution of the different soils of the Western Cape as well as a generalized soil description (Institute for Soil, Climate and Water, 2000)

Studies conducted in natural veld showed that soils associated with heuweltjies exhibit different physical and hydrological properties than surrounding soil, which results in altered growth patterns of individual plants, as well as a modification of plant community structure and productivity. According to Dean and Milton (1999) and Wiegand *et al.* (2000), the combined effect of modified soil physical and hydrological properties observed on the heuweltjies results in a significant change in the composition of plant species and plant functional types on and off heuweltjies. Ellis (2002) conducted a study in which he sampled 18 heuweltjies between Springbok and Oudtshoorn. His findings are quite exciting, with heuweltjies soils being more fertile, exhibiting higher pH and phosphorous values when compared to non-heuweltjie soils, as well as positive tests for free lime. These changes in soil properties, fertility as well as water availability through modifications of the micro scale topography, give rise to different vegetation patterns emerging on and off heuweltjies and subsequently leads to a distinction in biodiversity between heuweltjie and non-heuweltjie areas (Mucina *et al.*, 2006).

Although the mound shape of the heuweltjies is leveled by agricultural and cultivation activities such as ploughing, the effects of these heuweltjies are still apparent in cultivated landscapes. By studying aerial photographs, it appears that almost 60% of vineyards located in the Western Cape are characterized by heuweltjies (Shange *et al.*, 2006), as shown in Figure 1.1.

Portes and Ruyssen (1886) made a vague and general conclusion concerning soil and wine. They held firm that wines emanating from sandy soils are light and delicate, lacking strength and colour, but are perfumed and lively; limestone and chalk increases the alcoholic strength; and that iron and clay-rich soils will increase the depth and colour intensity of red wines. They also came to the conclusion that red wines favour reddish soils while white wine cultivars grows well on grey or yellow soils. Peynaud and Ribéreau-Gayon (1971) on the other hand found that clay soils produce less delicate, more acidic berries that are rich in tannins while limestone soils will result in berries having more odiferous constituents.

Carbonneau and Casteran (1987) demonstrated the effect soil type can have on the properties of a Cabernet Sauvignon wine in Bordeaux. The vines grown on a moist sand were ‘more balanced, soft and velvety’ while the vines grown on a dry, gravelly soil possessed better aromatic quality, colour intensity and quality as well as better structure, but also a higher acidity, bitterness and astringency. When white, yellow, orange and red light are reflected into the lower vine canopy and bunch zone, the ratio of red to far red wavelengths of light will be raised, giving rise to cytokinin dominance and more fruitfulness (Gladstones, 1992).

The incidence of the heuweltjies in vineyards has a significant influence on the growth, physiology and phenology of associated grapevines due to modifications of the soil physical, chemical and biological properties (Shange *et al.*, 2006), as well as nutrient status and general fertility. The effect on wine quality remains to be investigated, but the hypothesis is that due to the more fertile soils occurring on these heuweltjies, higher vine vigour and denser canopies will be induced that will lead to excessive shading of the interior leaves and bunches. This will inevitably alter the wine quality - whether favourably, or to the detriment thereof, remains to be seen.

Research done on heuweltjies in cultivated areas is in short supply. This study will contribute positively in that regard and give valuable insight into the soil properties and - processes still directly or indirectly influenced by the once flourishing termite population.

The overall aim of this study was to determine what the effects are of the persistence of heuweltjies in cultivated landscapes in Mediterranean and semi-arid climates on soil characteristics, grapevine vigour and wine quality, and what advantages and disadvantages, if any, this will lend to agricultural activities.

The objectives of this study in terms of the soil characteristics were:

1. To determine the underlying basic soil properties of heuweltjies and to compare it to the adjacent non-heuweltjie plots at four sites in two areas (Stellenbosch and the Robertson valley)
2. Measuring the soil water content of the soil on the heuweltjies and comparing the results with those of the adjacent soils in each of the two areas.
3. Establishing reasons for differences in physical, chemical and biological properties on and off the heuweltjie.

2. MATERIALS AND METHODS

2.1 Description of study areas

The two areas where studies were conducted are both situated on wine farms in the Western Cape. The first sampling area is located on the outskirts of Stellenbosch, at Ernie Els Wines (34° 00' 41.87" S, 18° 50' 45.79" E 172 m a.s.l.), and the other in Robertson, at Graham Beck Wines (33° 47' 52.45" S, 19° 47' 36.13" E, 204 m a.s.l.).

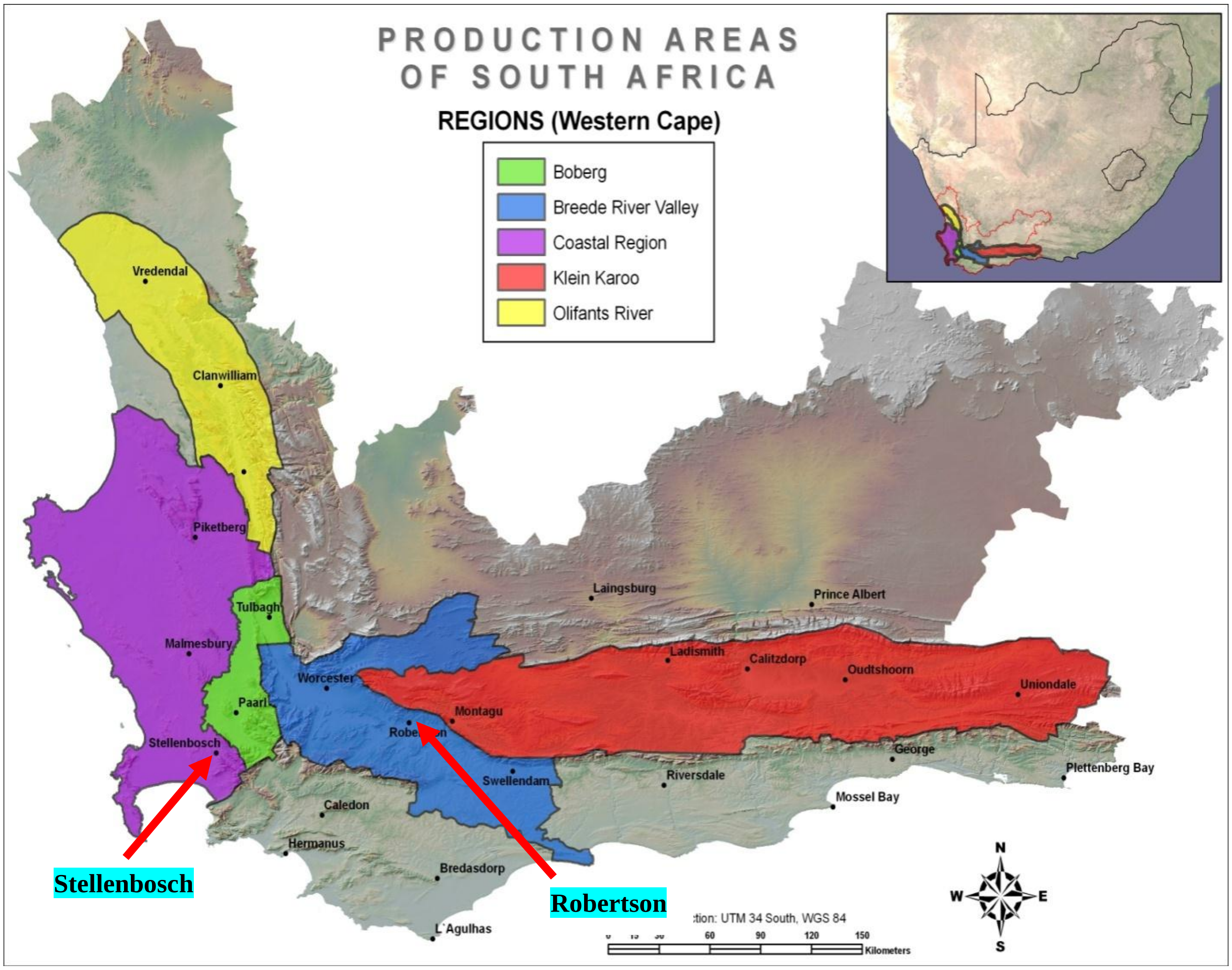


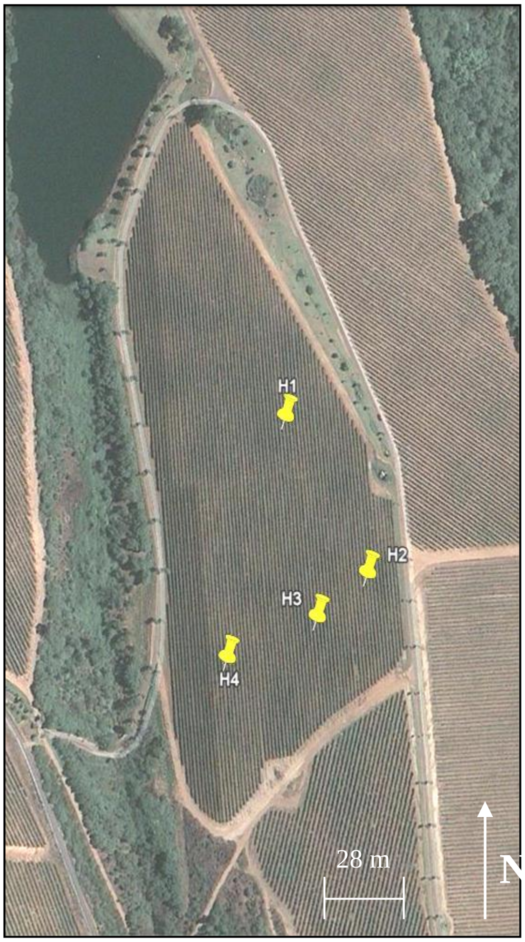
Figure 3.2: Location of Stellenbosch and Robertson in the Western Cape (adapted from http://www.sawis.co.za – viewed 30 June 2010). The figure shows the different wine production areas in the Western Cape Province.

The reason for the specific selection of these two areas is the difference in climate and soil characteristics between Stellenbosch and Robertson as well as the abundance of distinct heuweltjies that is found on both wine farms. Figure 3.2 shows the locations of the specific study areas as well as the different wine production areas in South Africa. It is useful to include the production areas, as the project takes place over two wine districts.

The following descriptions will be used to define the study area and its subdivisions:

- Stellenbosch and Robertson – **study areas**
- Different heuweltjies together with surrounding soils – **sites**
- Individual sampling points – **sampling plots**

2.1.1 Stellenbosch

a) 

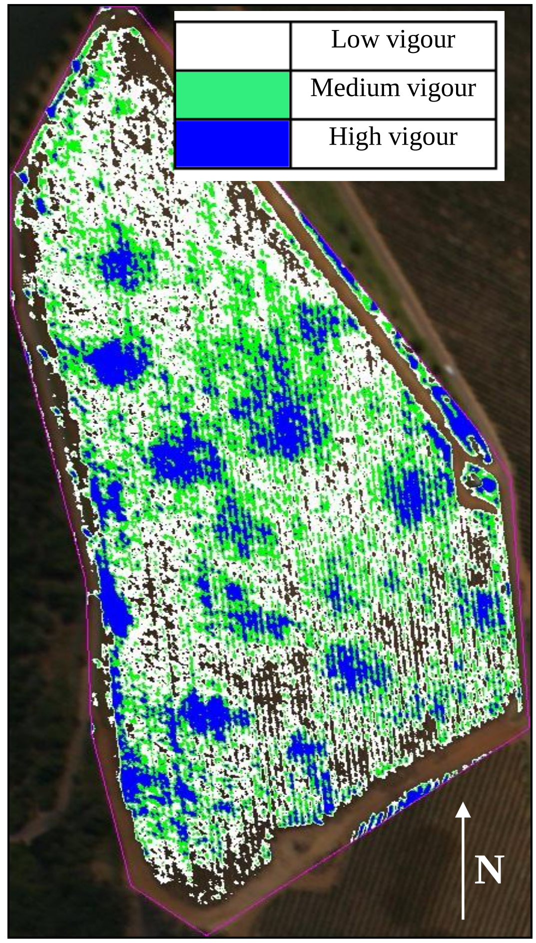
b) 

Figure 3.3: a) Location of specific sites where sampling and experimentation were done in the Stellenbosch study area (Google Earth, 10 May 2010) and b) a multispectral image of the Stellenbosch study area to better indicate the heuweltjies (A. Strever, Senior lecturer Viticulture, U.S., 2010, personal communication).

The orthorectified multispectral aerial image shown here in Figure 3.3(b) was classified with the software application Orthoviewer, by using a special Ratio Vegetation Index (RVI). Different colours were allocated to variations in vigour, as displayed in the legend.

2.1.1.1 Climate and terroir

Stellenbosch is classified as a relatively high rainfall area (600 – 800 mm pa) and receives its rainfall mainly in the winter months. It has hot dry summers and cool wet winters where frost is rarely a problem and falls under a

Mediterranean climate, ideal for viticulture and wine production. Rainfall and temperature are inversely proportional to one another. In the summer, daytime temperatures ranges from 26.3°C during the day to 15.6°C at night, while winter temperatures average from 15°C during the day to 6.6°C at night. Rainfall occurs mainly in winter (May - August) and is normally brought on by north-westerly winds (See Appendix 4.1). Snowfall does occur in the winter months and the presence of snow capped mountain peaks is not uncommon.

The Stellenbosch study area is situated high up on the northern slopes of the Helderberg Mountains, approximately 50 km from Cape Town. It falls under the Helderberg wine route, which is the oldest wine route in South Africa. Just a few kilometers from the eastern shores of False Bay, the vineyards on these slopes, hills and plains are subjected to cool and moisture-laden sea breezes from the Atlantic Ocean, combining the influences of both the mountain and maritime climate to produce some of the finest wines in South Africa (Anonymous, 2007). The effect of the sea breeze in summer is that it extends the ripening period, giving the grapes its uniqueness. Another prominent wind, the southeaster, locally known as the Cape Doctor, blows across the southwestern Cape during the spring and summer. It has a moderating effect on the vineyards and can lower the temperature by several degrees. By reducing humidity, it can also have a positive effect in terms of pest and diseases control. The specific study area reflects the unparalleled character of the Stellenbosch terroir and again demonstrates its ideal attributes to produce fine wines.

2.1.1.2 Geology, soil and vegetation

The Helderberg area forms part of the Cape Supergroup (Table Mountain group and Bokkeveld group) series which consists mainly of sandstone, granite, shale, greywacke and conglomerate (Anonymous, 2010). The soils where the vineyards are grown occur at altitudes of 150 – 200 m on steep slopes and are relics of a past, high rainfall tropical era. It is derived from Cape granite and qualifies as Oakleaf and Tukulu soil forms. The soils are highly weathered and very stable, well drained, with a high water-holding capacity and a high potential for grapevine cultivation (Anonymous, 2010).

The vegetation type of the Helderberg area is mainly comprised of Kogelberg Sandstone Fynbos (Mucina and Rutherford, 2006), which includes about 600 plant species like the Protea species, Pincushions and Cone bushes. Small patches of Boland Granite Fynbos are also to be found on the Helderberg, on the northern side where soils are deeper, granite derived and more fertile. In the wetter areas, Restios, Ericas and Watsonias flourish (Anonymous, 2010).

In this region, the occurrence of heuweltjies is very common. Figure 3.4 clearly depicts some of these landscape features in the natural veld and clearly indicates the distinction in vigour of the vegetation growing on and off the heuweltjies.

Figure 3.4: Occurrence of heuweltjies in natural veld near Stellenbosch.

2.1.1.3 Specific characteristics and management practices

The vineyard block where the study was conducted (block 21) is 5.13 ha in size and comprise of the Cabernet Sauvignon cultivar (Figure 3.5). Four heuweltjies together with its surrounding soil were selected where sampling and experiments took place. The unique terroir of the specific location makes it ideal for the cultivation of Cabernet Sauvignon. Cabernet Sauvignon performs better on soils that contain a high percentage of gravel and/or coarse material, so that optimum draining and aeration of the soil can be achieved. Heat is also absorbed and radiated more effectively which leads to earlier ripening (Clarke, 2001). A location with enough plant available water during ripening is preferred and slopes with a northern aspect are taken as optimal for Cabernet Sauvignon when grapevines are planted.

a) b) c)

Figure 3.5: Block 21 at different times during the season: a) May 2009; b) March 2010; c) June 2010. The arrows indicate some of the heuweltjies occurring in block 21.

Before the vineyard was established in 2003, soil preparation was done with a delve plough up to a depth of 750 mm. The grapevines were planted with an in-row spacing of 1.4 meters and a row spacing of 2.6 meters in a north-south direction on 101-14 rootstocks. The grapevines were trellised on the four wire Perold trellising system with movable foliage wires with a pole length of 2.4 meters above the soil surface. Micro irrigation with fixed spreaders is used in block 21, with a spreader spacing of 1.9 meters and delivery tempo of 5mm/hour. An alternation of cover crops is used: in 2009 Korog and Oats were used and in 2010 it was decided to plant White mustard or *Sinapsis alba*. The date of budburst for block 21 in 2009 was 8 October with a yield of 4.36 ton/ha.

Fertilizer was added to the soil in the following quantities:

- 2009 post harvest – 100 kg/ha KAN
- 2010 post harvest – 70 kg/ha KAN

In 2009 insects were released in the vineyard to biologically exterminate the mealybug that was found in block 21. *Coccidoxenoides perminutus* and *Cryptolaemus montrouzieri* were used as it is an effective natural enemy of the mealybug. The dates of rates are shown in Table 3.1.

Table 3.1: Release dates of the two insect species in experimental block 21.

	C. perminutus	***C. montrouzieri***
30-Oct-09	x	x
05-Nov-09		x
18-Nov-09	x	x
03-Dec-09		x
16-Dec-09		x

During the months of November and December, the Stellenbosch study area was subjected to very strong winds which caused severe wind damage (Figure 3.6). This had adverse effects on the grapevines and could have significantly influenced results obtained from the physiology measurements.

Figure 3.6: Indication of the extent of wind damage on the grapevines in the Stellenbosch study area.

2.1.2 Robertson

Figure 3.7: Location of specific sites where sampling and experiments were done in the Robertson study area (Google Earth, 10 May 2010).

2.1.2.1 Climate and terroir

The Robertson Wine Valley is situated on a continental shelf and is influenced by two great mountain ranges, the Langeberg in the north and the Riviersonderend in the south. The valley falls within a low rainfall area (150 – 400 mm pa) and can be classified as a semi-arid region. The study area is situated 7 km outside of Robertson in the Breede River Valley, on the border of the Little Karoo region about 175 km from Cape Town. It experiences hot, dry summers and cold winters with moderate rainfall. The average daytime summer temperature for Robertson is 28.1°C, while the average night time temperature in summer is 14.1°C. The average daytime temperature in winter is 21.1°C, while the average night time temperature is 7.4°C (Anonymous, 2008). Rainfall occurs primarily in the winter months (May - August) and is mainly brought on by north-westerly winds (See Appendix 4.2). Hailstorms do tend to occur in the summer months and can be devastating to crops.

The landscape is reasonably flat and the terroir is essentially determined by differences in soil type. The landscape changes to rolling hills towards the foothills of the Langeberg mountain range. The climate of the area together with the mineral rich soils makes this area perfect for the production of quality wines.

2.1.2.2 Geology, soil and vegetation

The study area is surrounded and bordered by Sandstone Mountains and ridges with underlying Malmesbury greywacke and mudstones and covered by Quaternary boulder beds (Hall and Visser, 1984). The area surrounding the sampling location is underlain with Malmesbury shale and Cape granite on the northern side with Bokkeveld and Witteberg quartzite making up the geology on the south side. The middle and lower reaches of the Breede river valley, where the study area is situated, is predominantly underlain by Devonian Bokkeveld shales. The soils on the farm used for viticulture are mainly alluvium that contains colluvial deposits. They are red-brown, calcareous in some parts, and belong to the Augrabies, Valsrivier, Brandvlei, Oudtshoorn and Oakleaf soil forms. The high concentration of lime in the soil results in a lower temperature, allowing less heat to reach the vine through radiation, thereby delaying ripening. The lime in the soil makes Robertson Wine Valley very suitable for the cultivation of Chardonnay and is therefore a prime producer thereof. The soils together with the warm climate promote vigorous growth of the grapevines as well as high yields. In the warm climate of Robertson, more emphasis is placed on less fertile soil to prevent luxurious growth and thus promotes less vigour and keeps yields low (Clarke, 2001) This again has a positive effect in terms of quality.

The countryside that surrounds the study area is covered with indigenous fynbos and the effect of heuweltjie incidence on vegetation in its natural condition can be clearly seen in Figure 3.8.

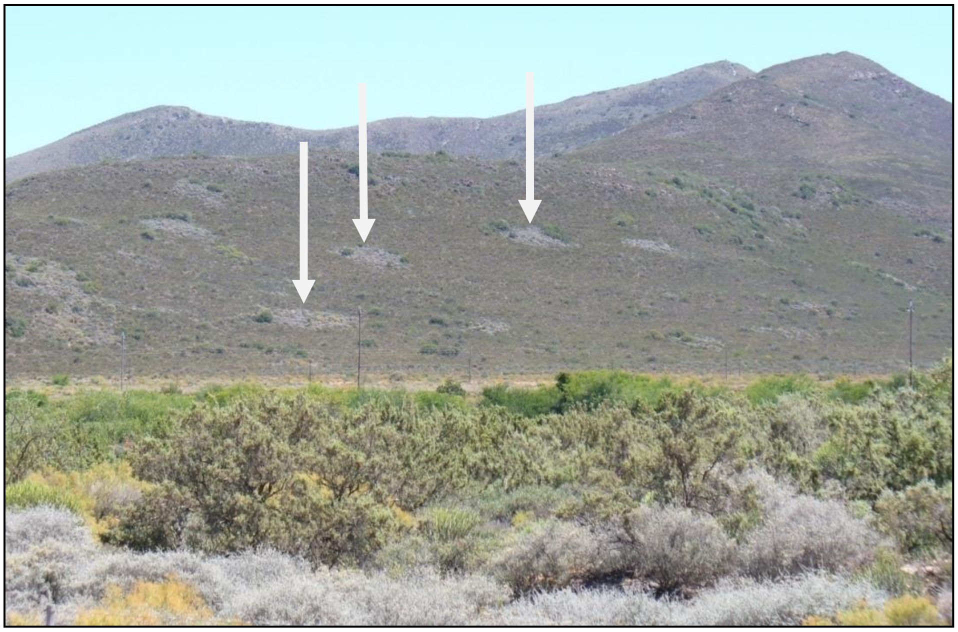


Figure 3.8: Occurence of heuweltjies in natural veld in Robertson.

2.1.2.3 Specific characteristics and management practices

Vineyards are planted on 169 ha of the study area's property and out of that, 39% is under Chardonnay, 27% under Shiraz, 12% under Pinot noir and 8% under Cabernet Sauvignon. A very small percentage is made up of Pinotage, Merlot, Cabernet franc, Ruby Cabernet, Sangiovese, Viognier, Muscat de Alexandrie and Sauvignon blanc.

The vineyard blocks where the experiments were conducted, consisted of Shiraz and Chardonnay (blocks 4, 5 and 6). The farm does contain a very small percentage Cabernet Sauvignon, but no heuweltjies occur within these blocks. However, distinct heuweltjies appears in the Shiraz-Chardonnay blocks and to make comparison with the Stellenbosch possible, four heuweltjies together with its surrounding soil were selected only in the Shiraz parts of the blocks. All sampling and experiments took place on these sites. Shiraz grows very well on cool slopes that are adequately supplied with soil water. The cool conditions delay ripening and are preferred to induce that unique smoky, spicy, pepper character of Shiraz. Thus middle slopes that face east with a north-south row direction is optimal.

Before planting of the specific grapevines, soil preparation was done to create a favourable environment for the grapevine roots in relation to air, moisture and soil, thus promoting growth and production, ensuring maximum potential is gained from the soil. The soil was deep ripped in the direction of the slope of land up to a depth of 800 mm, followed by a cross rip action in the row direction with a 1.2 meter single tine cutting width of 600 - 750 mm. The vines were then planted in July 1997 with an in-row vine spacing of 1.2 meters and a row spacing of 2.4 meters on Richter 110 rootstock. The vines were trellised on the classic four wire Perold trellising system with the length of the poles reaching 1.5 m above the soil surface. Drippers were installed for irrigation with one meter spacing and a delivery tempo of 4L/hour. A cover crop is planted every year, but alternates every second year between Koorog and Oats (see Figure 4.3, Chapter 4). The dimensions of the specific blocks are as in Table 3.2:

Table 3.2: Dimensions of Shiraz experimental blocks 4, 5 and 6 in the Robertson study area.

	Size (ha)	Vine spacing	Row spacing	Vines planted	Yield (ton/ha)
Block 4	1.62	1.2 m	2.4 m	5624	10
Block 5	2.11	1.2 m	2.4 m	7325	10
Block 6	2.46	1.2 m	2.4 m	8541	10

As indicated in Table 3.3, gypsum was added to all three blocks in 2004, after planting of the vines. This was done to counter the high Na content of the soils. Na substitutes the Ca present in gypsum which allows for the formation of Na_2SO_4, which in turn is soluble in water and can leach out. A nitrogen fertilizer is also applied every year at specific stadia in the phenolic cycle to replace some of the nutrients taken from the soil during the growing season (Table 3.3).

Table 3.3: Fertilizer applied to blocks 4, 5 and 6 in the Robertson study area.

Site	Year of application	Product	Post harvest (kg N/ha)	Budburst (kg N/ha)
Block 4	2004	Gypsum - 7 ton/ha once off after planting	-	-
	2009, 2010	UREUM 46 %	40	0
Block 5	2004	Gypsum - 7 ton/ha once off after planting	-	-
	2009, 2010	UREUM 46 %	40	20
Block 6	2004	Gypsum – 7 ton/ha once off after planting	-	-
	2009, 2010	UREUM 46 %	40	20

It needs to be pointed out that a massive hail storm occurred in Robertson in the month of February 2010 (Figure 3.9). It damaged the canopy and grape bunches and therefore all further physiology readings would have been futile. Fortunately the grapes for the study were harvested before that time.

a) b)

Figure 3.9: Indication of the extent of hail damage inflicted on the grapevines in the Robertson study area.

2.2 Soil properties

2.2.1 Morphological soil properties

2.2.1.1 Soil sampling

Soil samples were obtained to determine the physical and chemical properties of the soils that occur on and off heuweltjies. More samples were taken from a greater variety of sites in Stellenbosch than in Robertson, due to the proximity to the University campus. The aim of the study was to differentiate between heuweltjies and its adjacent soils and not between Stellenbosch and Robertson per se.

We selected a Cabernet Sauvignon vineyard block at the Stellenbosch study area that contained heuweltjies which stood out conspicuously from the surrounding soils and that could be observed on an aerial photograph. A block that contain fourteen heuweltjies was chosen, where ultimately four were selected, along with their adjacent 'off heuweltjie' sites. The same was done in the Robertson study area, except in this case, three blocks Shiraz vineyard were chosen as sites for sampling.

Soil sampling took place during the winter months (June and July) as it was previously determined that it is the most stable period for soil biogeochemical (nutrient) sampling as most soil manipulation activities takes place during spring and late summer, as was the case in the study of Shange *et al.*, (2006). Samples were taken at five positions on the heuweltjie in both the Stellenbosch and Robertson study areas – on the crest of the heuweltjie, on both edges of the heuweltjie and between the crest and the edges on both sides - as well as at two spots surrounding the heuweltjie. Because of the fact that the Stellenbosch vineyard block occurs on a slope, and nutrients might have been prone to move down slope over the time, we found it necessary to take samples at the top of the slope (south side) as well as at the bottom (north side). Samples were taken at five depths: 0 - 20 cm, 20 - 40 cm, 40 - 60 cm, 60 - 80 cm and 80 – 100 cm using a Thompson auger. Samples were stockpiled in plastic bags until analysis, and the remainder was kept for the duration of the study.

Table 3.4: The outlay and the designation of the specific sampling sites in the Stellenbosch and Robertson study areas.

		Heuweltjie					**Non-heuweltjie**	
Study area	**Heuweltjie**	**Crest**	**Mid south**	**Mid north**	**Edge south**	**Edge north**	**Off south**	**Off north**
Stellenbosch	SH1	SH1C	SH1Ms	SH1Mn	SH1Es	SH1En	SH1Os	SH1On
	SH2	SH2C	SH2Ms	SH2Mn	SH2Es	SH2En	SH2Os	SH2On
	SH3	SH3C	SH3Ms	SH3Mn	SH3Es	SH3En	SH3Os	SH3On
	SH4	SH4C	SH4Ms	SH4Mn	SH4Es	SH4En	SH4Os	SH4On
		Crest			**Edge**		**Off**	
Robertson	RH1	RH1C	-	-	RH1E		RH1O	
	RH2	RH2C	-	-	RH2E		RH2O	
	RH3	RH3C	-	-	RH3E		RH3O	
	RH4	RH4C	-	-	RH4E		RH4O	

The same procedure of sampling was followed in Robertson, except that fewer sampling points were chosen. Samples were taken at three positions on the heuweltjie – on the crest and on the edge, and one position in the adjacent soil surrounding the heuweltjie. The vineyard blocks is not planted on a slope, therefore less variation was expected in nutrient levels.

2.2.1.2 Profile descriptions

In Stellenbosch we encountered a problem with the digging of the profile pits by the use of an excavator. The size of the excavators were all too big to fit in between the grapevine rows, so the holes had to be dug using man power and shovels. A profile pit of 1.2 m depth was dug on the crest and the edge of the heuweltjie, as well as in the adjacent soil surrounding the heuweltjie at each of the four sites. The same method was followed in Robertson, except for the fact that a small excavator was hired to dig all of the pits.

Terrain and morphological properties of the soils on and off the heuweltjie were examined and the soils were described and classified according to the South African Soil Classification System (See Appendix). Photographs were taken of the specific profile pits to indicate visual differences between the soils on and off the heuweltjies. During classification of the soils at four sites in both Stellenbosch and Robertson, a pattern developed and it was very clear, even by visual investigation, that there were major differences in soil physical as well as chemical properties on and off heuweltjies. By closer examination of the photographs, it is apparent that termites are no longer active in the soil due to the disturbance of cultivation and soil tillage.

<u>2.2.1.2.1 Stellenbosch</u>

Two soil forms occur in the sample block. The crests of the heuweltjies all displayed the same physical properties and were classified as Oakleaf, while the edges as well as the surrounding soils had the same general attributes and were classified as Tukulu. The soils on the crest of the heuweltjies are well drained and showed no signs of wetness. This allows for a deeper root system which enables the vine to be buffered against fluctuations in soil water. The subsoil of surrounding soils showed signs of wetness and grey mottles are visible. The A-horizons of both the Oakleaf and Tukulu soil forms exhibit a dark colour because of the accumulation of organic material.

There is a significant change in clay content and texture from the A horizon to the B horizon on the crests of the heuweltjie, which led to the classifaction of the B horizons as luvic. An important factor that attributed to the clay accumulation of the B horizon is bioturbation. Termites bring clay into their nest and mix it with faeces to construct tunnels and galleries in their nest. Thus because of the distinct change in texture and the fact that the B horizons are luvic, the soil families on the crests were all classified as Oakleaf 1120.

The heterogeneous colour of the soils on the crests of the heuweltjies could be attributed to the presence of clay cutans as well as channel fillings with earthworm cast, according to Dawez-Gromadzki (2005). On the edges of the heuweltjies as well as on the surrounding soils, the normal process of clay movement/’lessivage’ takes place and is the main reason for the change in clay content from the A to B horizon. The B horizons are all luvic and are classified as Tukulu 1120. Photo illustrations of the soils on and off the heuweltjie are displayed in Figure 3.10.

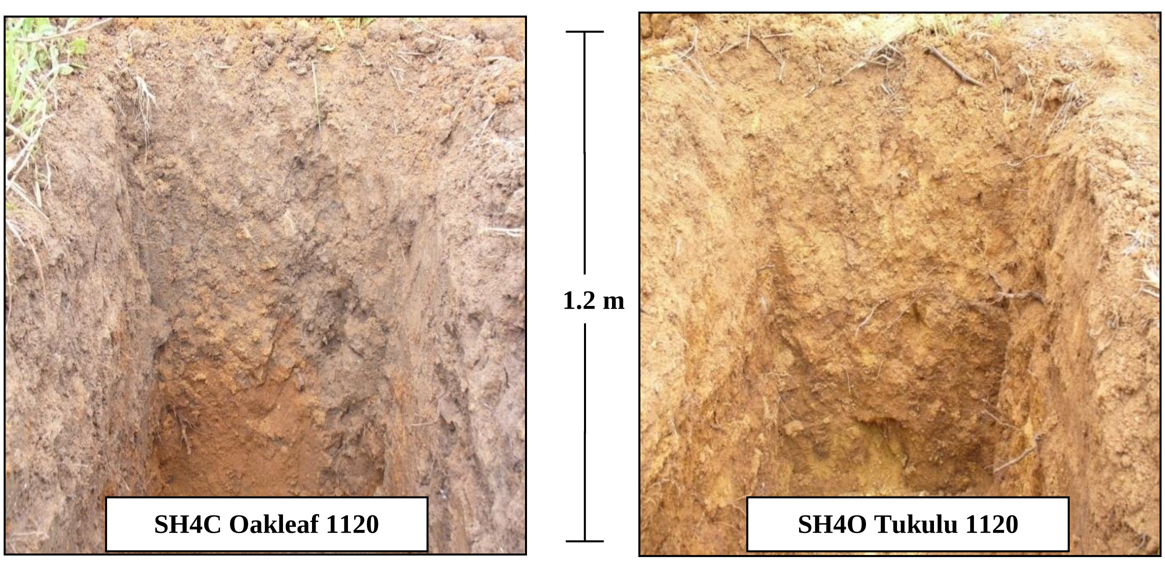


Figure 3.10: Photo illustrations of the soils on and off the heuweltjie respectively, in the Stellenbosch study area.

2.2.1.2.2 Robertson

Because of the fact that sampling took place in three adjacent vineyard blocks (i.e. a larger area) in Robertson, much more variation was found in the soils in comparison with the Stellenbosch sites. The soils are both alluvial and colluvial in origin and are relatively young. The soils were deposited by the Breede River (the study site is situated on a terrace of the river) and comprise of a high sand fraction.

Three of the four heuweltjie crest soils (RH1C, RH3C and RH4C) that were investigated exhibit the characteristics of an Augrabies soil form, while H2C is a prominent Brandvlei. The A-horizons are not bleached, due to higher organic material contents on the crest of the heuweltjies, and the clay content of these soils is very low, both in the A- and B-horizons. Therefore the soils are classified as Augrabies 1110 families. All four these soils have a high concentration of calcium carbonate and lime concretions are present. Much of the natural calcrete hardpans have been destroyed by ploughing and soil tillage but remnants are still visible in RH2C (Figure 3.11).

a)  b) 

Figure 3.11: Remnants of a calcrete hardpan on H2C in the Robertson study area.

Termites have the ability to accumulate lime in their nests. The food (leaves, twigs etc.) that they bring into the nest as well as their faeces contribute to the accumulation of bases. The low rainfall contributes to the low degree of leaching and the accumulation of free lime in the soil leads to the formation of calcium carbonate-rich horizons. This happens over thousands of years under very specific climatic conditions.

Due to the absence of termite induced changes in soil properties in the adjacent surrounding soils, it was speculated that no carbonates would be present in the adjacent soils surrounding the heuweltjies. This was confirmed by testing the soils with HCl. Only the B horizon of RH3O showed any sign of carbonates. Four different soil forms could be distinguished at the sites surrounding the heuweltjies: Oakleaf 2110 (RH1O), Oudtshoorn 2110 (RH2O), Augrabies 2110 (RH3O) and Valsrivier 2221 (RH4O). A partially destroyed dorbank is present in RH2O, approximately a meter from the surface. Photo illustrations of the soils on and off the heuweltjie are displayed in Figure 3.12.

Figure 3.12: Photo illustrations of the soils on and off the heuweltjie in the Robertson study area

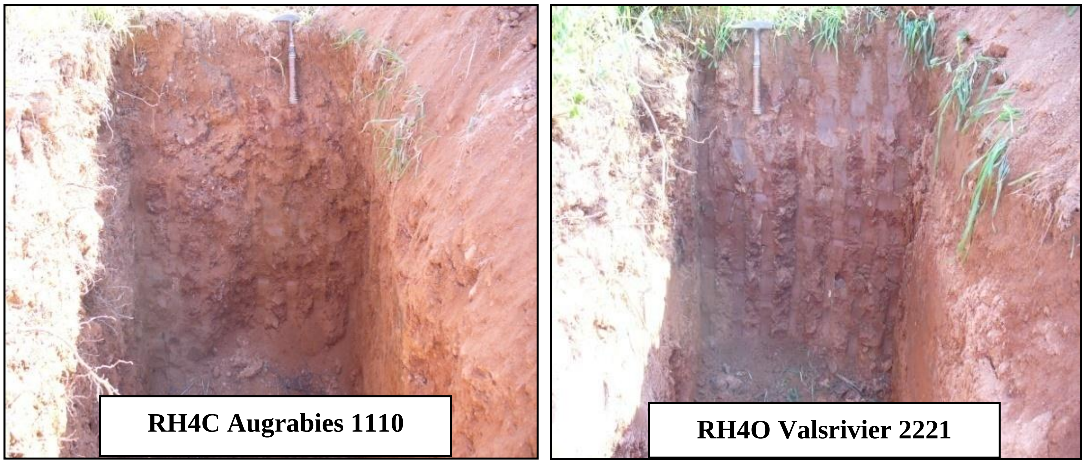


Figure 3.12 (Continued): Photo illustrations of the soils on and off the heuweltjie in the Robertson study area

2.2.2 Physical analysis

2.2.2.1 Bulk density

The bulk density of a soil is an important property that can provide valuable information relating to the physical condition of the soil. It was determined using the core method modified from Blake and Hartge (1986), by using a smaller core (diameter of 4cm vs. 4.7 cm of original core). According to the core method, a volume of soil is removed from the soil profile *in situ* using a steel cylinder of a known volume where after the soil is dried. Thus, by having the volume of the cylinder and the mass of the dried soil, bulk density can be determined.

2.2.2.2 Soil water content

Without taking into account the rainfall and irrigation, soil texture will determine the water-holding capacity of the soil and thus in a sense control the amount of water in a soil profile. The soil water content was measured using a CPN neutron water probe. Monthly readings were taken both at Stellenbosch and Robertson. Readings were carried out over a depth of 1 meter in increments of 15 cm. Micro irrigation is used in Stellenbosch with a delivery tempo of 5.5 mm per hour and in Robertson all sites are under drip irrigation with each dripper delivering water at a tempo of 4L per hour.

Calculations of evapotranspiration were done according to the water balance equation (Hillel, 1980):

$$ET = P + I - \Delta S$$

where ET is evapotranspiration, P is precipitation, I is irrigation and ΔS is the change in soil water content.

Four access tubes were installed in the soil on the heuweltjie and two in the adjacent soil surrounding the heuweltjie. PVC tubes were used and the probe was calibrated for each site. Calibration of the neutron probe was done by taking soil samples with a Thompson auger at the same depths that readings took place, weighing it in the wet condition and then drying it for 24 hours at 105C°, thus measuring their gravimetric water content over a period of time. This was done five times over the season to ensure a good variation in soil water content and to ensure that we have a very wet as well as a very dry reading. With the already available bulk density data, the volumetric water content at each depth was calculated.

2.2.2.3 Texture analysis

Textural analysis of the soils occurring on and off the heuweltjies was done at two sites at each location. The sand fractions (2 – 0.05 mm) were separated through sieving, according to the method described by Gee and Bauder (1986), while the silt-clay fractions (<0.05 mm) were determined using the pipette method (Gee and Bauder, 1986).

The fraction of sand, silt and clay in the soil determines its textural classification. Once the percentages of the sand, silt and clay in the soil are known, the texture class can be determined from the texture triangle.

2.2.3 Chemical analysis

Compared to the physical properties, a different approach was used as far as the sampling for the chemical properties is concerned. A more detailed positional sampling strategy was adopted at Stellenbosch where the heuweltjies occurred in a block with a slight slope (9%). We expected the upper and lower side of the heuweltjies to exhibit different trends, based upon a contention that lateral flow of water would result in displacement of nutrients further down the slope (F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication). This was not the case at Robertson, where the slope was negligible, and we did not consider the different sides of the heuweltjies to be substantially different.

2.2.3.1 pH in water and KCl

Soil pH indicates the activity of hydrogen ions in a soil suspension in either 1 mol.dm^{-3} KCl or de-ionized water. By using a concentration of 1 mol.dm^{-3} KCl, a stable reading is obtained. In the soil, there can be much variation in salt concentration due to the effect of irrigation water, fertilizer residues and microbial decomposition of organic material. Therefore KCl can be used instead of water to mask that variation. The activity of hydrogen ions in 1 mol.dm^{-3} KCl can be as much as 1 or 2 pH units lower than that measured in water, using the same soil:water ratio, that of 1:2.5. The pH was determined both in water and KCl, according to the method described by White (1997).

2.2.3.2 Electrical conductivity

The electrical conductivity (EC) of the soils was determined according to the saturated paste method described in Page *et al.,* (1982).

2.2.3.3 Extractable cations

Extractable cations Ca^{2+}, Mg^{2+}, K^{2+} and Na^{+} were determined by the ammonium acetate extract method according to Non-affiliated Soil Analysis Work Analysis Committee (1990), thereby reflecting the soil's nutrient status. The Stellenbosch samples were treated with ammonium acetate with a pH of 7. For the Robertson samples however, the pH of the ammonium acetate extractant was increased to 8.5 by adding Ammonia. This was done due to the high calcium carbonate content and pH of the Robertson soils. In calcareous soils, the original Ammonium acetate extraction at pH 7, over estimates the exchangeable calcium in the soil. Results were obtained in mg/l and presented in cmol/kg.

2.2.3.4 Extractable Phosphorus

The phosphorous content of the soil was determined by using the Bray 2 method (Non-affiliated Soil Analysis Work Committee, 1990). The Bray procedure developed by Bray and Kurtz (1945) is a method used to extract acid soluble and adsorbed or available and reserve phosphates present in soil. The Bray 2 solution consists of 0.1 M HCl and 0.03 M NH_4F. The extraction of P by this procedure is based on the solubilisation effect of H^+ on soil P and the ability of F^- to lower the activity of Al^{3+}, and to a lesser extent that of Ca^{2+} and Fe^{3+} in the extraction system.

2.2.3.5 Total carbon and nitrogen

The total carbon and nitrogen percentages of the soil were determined by dry combustion *via* the EuroVector Elemental Analyzer, according the specifications of the EuroVector instruction manual (Instruction manual of EuroVector, 2002).

2.2.3.6 Organic carbon

According to Schollenberger (1927), organic material in soil can be oxidized by treating it with a hot mixture of $K_2Cr_2O_7$ and sulfuric acid as illustrated by the equation:

$$2Cr_2O_7^{2-} + 3C + 16H^+ = 4Cr^{3+} + 3CO_2 + 8H20$$

After the reaction is completed, the excess dichromate is titrated with iron (II) ammonium sulfate hexahydrate. By assuming that the soil organic matter has an average valence of zero, it is calculated that the reduced dichromate is equivalent to the organic carbon present in the sample. Soil samples were analyzed for organic carbon percentages according to the Walkley-Black method, as described by the Non-affiliated Soil Analysis Work Committee (1990).

2.2.4 Statistical analyses

For the analysis of the physical and chemical soil characteristiscs, factorial ANOVA's was carried out, with soil depth and the type of plot (heuweltjie versus non-heuweltjie) as independent variables, after testing for normality using the Shapiro-Wilks W-test, using Statistica Release 9. This was followed by a Fisher's LSD posthoc test.

3. RESULTS

While soil sampling took place, a clear distinction could be made between the colour of the heuweltjie soils and that of the surrounding soils (Figure 3.13). This can be attributed mainly to the fact that a higher percentage of organic carbon is present in the heuweltjie soils. The reason for it being so will be discussed later in the Chapter.

Figure 3.13: Differences in topsoil colour of a Stellenbosch heuweltjie and its surrounding soil respectively.

3.1 Physical properties

3.1.1 Bulk density

3.1.1.1 Stellenbosch

Upon examination of the average bulk density values, it is clear that no significant difference exists between HC and HO at any of the depths (ANOVA followed by Fisher's LSD posthoc test; $p > 0.05$; results shown in Figure 3.14). The average bulk density of HC is 1.55 g.cm^{-3} compared to 1.54 g.cm^{-3} of HO and the difference was insignificant ($p > 0.05$). It is only when differences between the specific depths are investigated, that some sort of pattern can be derived. The only significant increase ($p < 0.05$) in bulk density with depth, occurred from the 0-20 cm to 20-50 cm sample. In both the HC and HO plots bulk density increased with depth increments; from an average low of 1.34 g.cm^{-3} in the 0-20 cm samples of HC, up to 1.65 g.cm^{-3} in the 80-100cm samples of HC. In the HO plots bulk density increased from 1.39 g.cm^{3} to 1.64 g.cm^{3}, up to a depth of 80 cm from where it decreased to 1.51 g.cm^{3} up and to 1m depth. On HC, a gradual increase in bulk density took place up to 80 cm where it reached a plateau of 1.65 g.cm^{-3} at 1m depth.

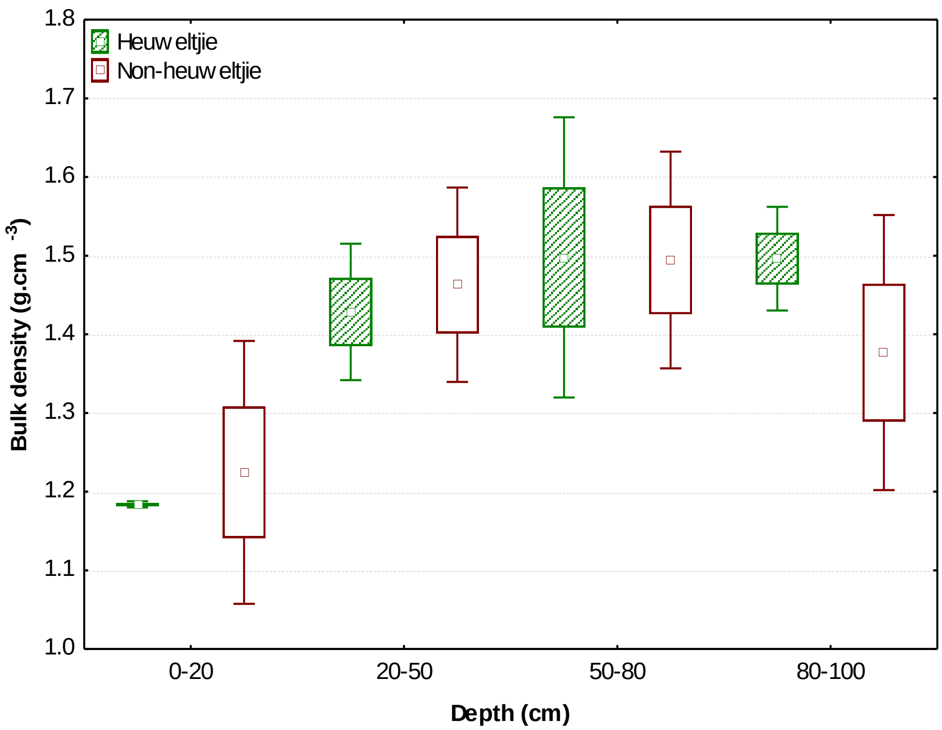


Figure 3.14: Bulk density of the soils occurring on the heuweltjie and non-heuweltjie plots in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

<u>3.1.1.2 Robertson</u>

The average bulk density of HC is 1.44 g.cm^{-3} compared to 1.49 g.cm^{-3} of HO. No significant difference existed between the HC and HO plots at any of the depths ($p > 0.05$), with HO plots displaying slightly higher bulk density values than HC plots. The bulk density values per depth average from 1.34 g.cm^{-3} in the 50-80 sample to 1.59 g.cm^{-3} in the 80-100 cm sample for the HC plot; while values averaged from 1.41 g.cm^{-3} in the 0-20 cm sample to 1.57 g.cm^{-3} in the 80-100 sample for the HO plots. HC and HO exhibit the same trend and bulk density values are related to depth. Bulk density increase with depth increments up to 50 cm, below which a slight drop in bulk density is discerned, with lower values displayed in the 50-80 cm samples. The density increases again in the 80-100cm sample (Figure 3.15).

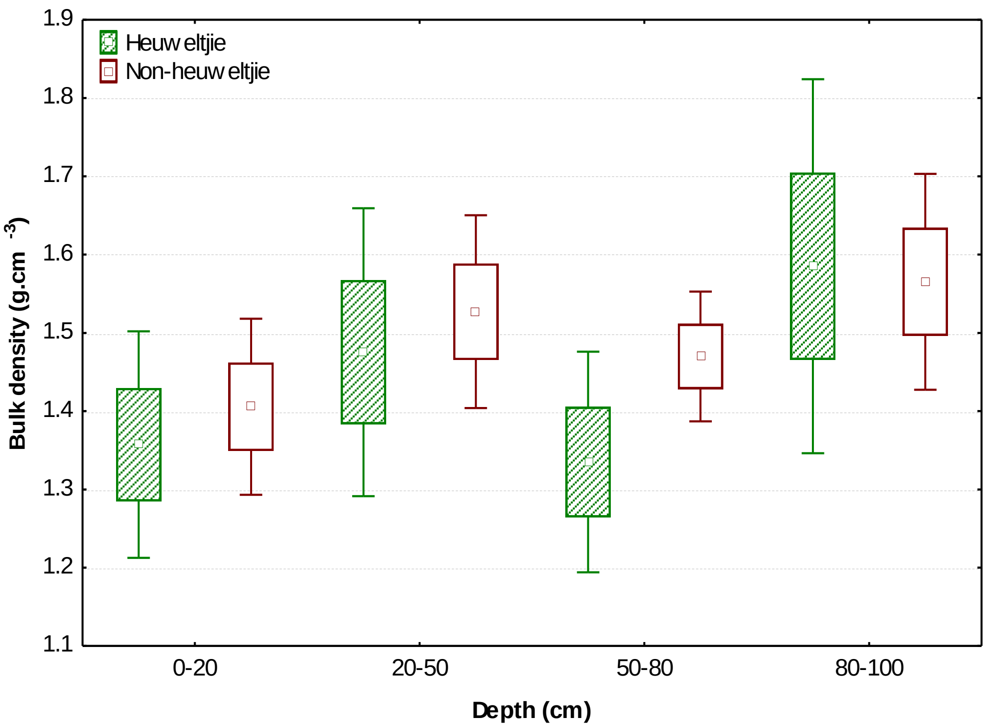


Figure 3.15: Bulk density of the soils occurring on the heuweltjie – and non-heuweltjie plots in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.1.2 Texture analysis

3.1.2.1 Stellenbosch

No distinct pattern concerning depth can be observed in the clay percentages of the heuweltjie soils. The process of bioturbation by the termites seems to counteract lessivage and a more homogeneous distribution of clay is observed. The clay percentages of the soils on the heuweltjie are significantly higher than that of the adjacent surrounding soils, with a minimum value of 25.96% in the topsoil (0-20cm) of S4O and a maximum value of 40.78% in the subsoil (80-100cm) of S1C (Table 3.5)

Table 3.5 displays the different textural classes of the soils occurring on the Stellenbosch sites. Through careful study of the kurtosis and skewness values, the conclusion can be made that a high degree of mixing occurred in the sand fractions of the soil during the time of soil transport and deposition.

Table 3.5: Texture analysis of the soils associated with heuweltjie and non-heuweltjie plots in the Stellenbosch study area.

Plot	Soil type	Depth (cm)	Skewness	Kurtosis	Very coarse sand (%)	Coarse sand (%)	Medium sand (%)	Fine sand (%)	Very fine sand (%)	Coarse silt (%)	Fine silt (%)	Clay (%)
					> 2 mm	2 - 0.5 mm	0.5 - 0.25 mm	0.25 - 0.106 mm	0.1 - 0.053 mm	0.05 - 0.02 mm	0.02 - 0.002 mm	<0.002mm
H1C	Oakleaf 1120	0-20	0.05	1.87	7.99	7.92	8.92	10.2	6.58	14.57	12.47	28.2
H1C	Oakleaf 1120	40-60	0.08	1.82	8.34	6.31	7.59	8.78	5.53	11.05	10.3	38.96
H1C	Oakleaf 1120	80-100	0.09	1.82	8.63	5.64	7.65	8.54	5.12	6.11	14.54	40.78
H1E	Tukulu 1120	0-20	-0.14	1.96	7.62	6.3	10.07	12.65	7.51	11.45	14.66	27.09
H1E	Tukulu 1120	40-60	0.08	1.74	9.52	5.88	10.3	6.44	9.26	9.28	9.22	36.86
H1E	Tukulu 1120	80-100	-0.02	1.83	9.05	5.8	9.22	10.34	6.9	13.82	9.26	34.45
H1O	Tukulu 1120	0-20	0.12	1.96	8.28	9.47	9.62	10.72	5.52	10.27	16.23	26.19
H1O	Tukulu 1120	40-60	0	1.94	7.97	7.77	9.9	11.4	6.18	8.22	11.73	33.41
H1O	Tukulu 1120	80-100	0.03	1.81	7.83	7.62	8.38	9.6	7.53	14.58	6.66	34.89
H4C	Oakleaf 1120	0-20	0.24	1.87	9.98	9.44	7.28	9.53	5.14	6.98	20.7	28.6
H4C	Oakleaf 1120	40-60	0.09	1.88	7.07	7.44	7.2	9.19	4.93	10.68	13.65	37.07
H4C	Oakleaf 1120	80-100	0.11	1.84	7.82	8.02	7.1	9.49	5.52	8.39	12.11	39.04
H4E	Tukulu 1120	0-20	0.14	1.8	9.61	8.28	7.32	10.11	5.71	11.39	17.9	27.13
H4E	Tukulu 1120	40-60	0.05	1.87	7.11	8.18	7.49	10.18	5.74	11.44	12.43	35.11
H4E	Tukulu 1120	80-100	0.16	1.86	6.41	6.71	5.71	7.19	4.17	7.94	22.96	36.55
H4O	Tukulu 1120	0-20	0.15	1.91	9.65	9.29	9.26	10.89	5.27	8.07	17.66	25.96
H4O	Tukulu 1120	40-60	0.12	1.83	7.18	6.67	6.36	8.08	4.86	10.45	19.16	34.27
H4O	Tukulu 1120	80-100	0.15	1.81	7.38	6.55	5.99	7.6	4.84	10.96	17.86	35.8

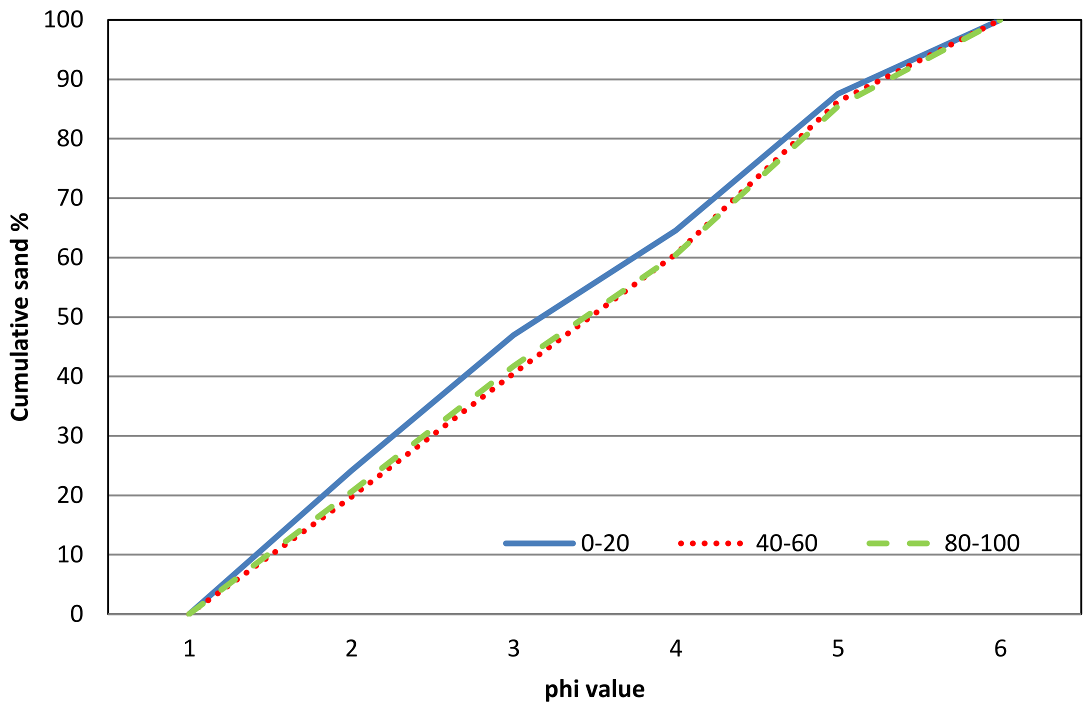
When the heuweltjie soils are compared to the surrounding soil, differences in the distribution of sand particles through the soil profile are trivial. Figure 3.16(a) indicates a very small variation in the distribution in comparison to almost no sand mixing that occurred in Figure 3.16(b). This small, yet vital difference can be amounted to bioturbation by termite activity that takes place in the heuweltjie soils and is especially noticeable in the 0-20 cm soil samples.

We speculated that there might be a fair degree of mixing that occurred in the sand fractions due to termite activity. Therefore graphs of cumulative sand percentage against depth were drawn up to indicate the extent to which mixing of the sand has taken place. Here the heuweltjie and surrounding soil are portrayed and it is clear that a difference can be distinguished between the heuweltjie and non-heuweltjie soils.

3.1.2.2 Robertson

The soils of the Robertson study area were much lower in clay content than those of Stellenbosch, due to the difference in parent material from which the soils are derived. The sand fraction made up the bulk of the soil which contributes to a higher water infiltration tempo. The clay values range from 8.97% in the subsoil of R2C to 26.57% in the subsoil of R4O. Upon examination of Figure 3.17(a and b), it is clear that a significant difference occurs in the sand particle distribution of the heuweltjie soils in comparison to the adjacent, surrounding soils and it is fair to say that a higher degree of mixing occurred in the sand fraction of the heuweltjie soils than non-heuweltjie soils. Table 3.6 displays the different textural classes of the soils occurring on the Robertson sites.

a)



b)

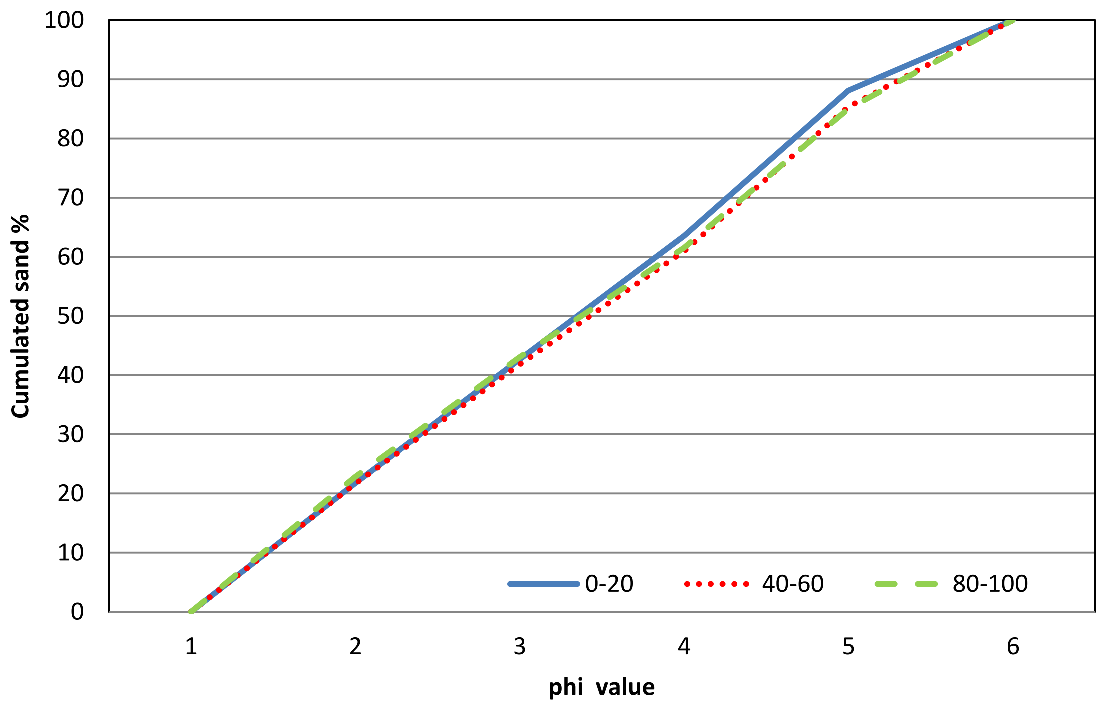
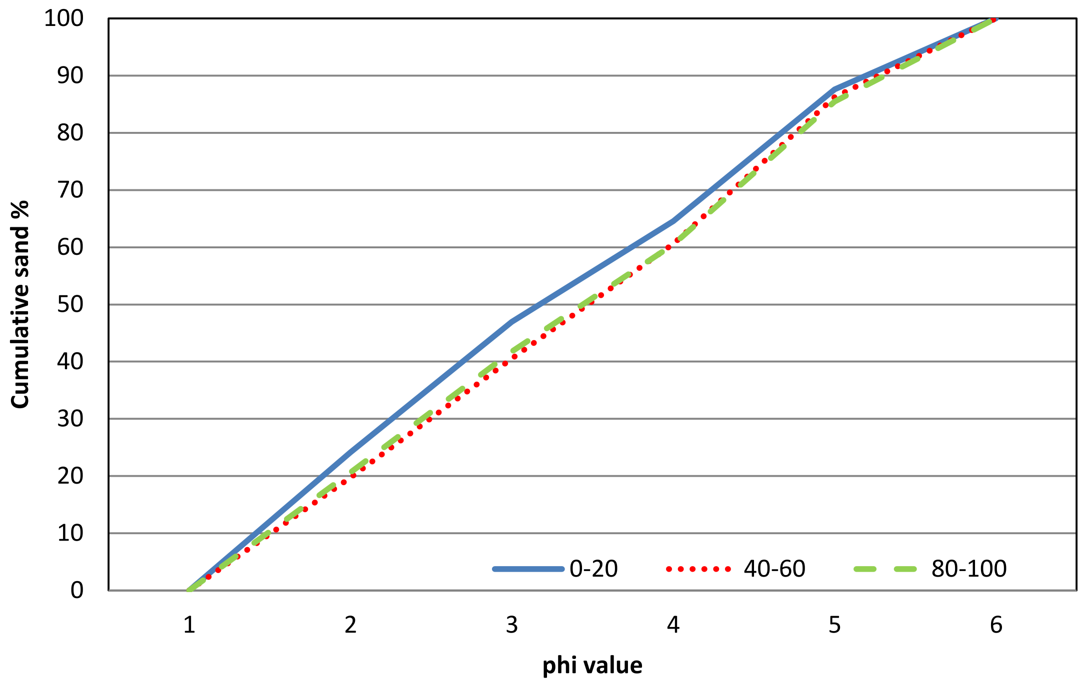


Figure 3.16: Degree of mixing of the sand fractions by indicating cumulative sand percentages in different soil depths in a) heuweltjie soil in comparison to b) non-heuweltjie soil in the Stellenbosch study area. The size of the sieves (in mm) used for sand fraction separation is converted via the logarithmic scale and is shown here as the phi value.

Table 3.6: Texture analysis of the soils associated with heuweltjie and non-heuweltjie plots in the Robertson study area.

Plot	Soil type	Depth (cm)	Skewness	Kurtosis	Very coarse sand (cm)	Coarse sand (cm)	Medium sand (cm)	Fine sand (cm)	Very fine sand (cm)	Coarse silt (cm)	Fine silt (cm)	Clay (%)
					> 2 mm	2 - 0.5 mm	0.5 - 0.25 mm	0.25 - 0.106 mm	0.1 - 0.053 mm	0.05 - 0.02 mm	0.02 - 0.002 mm	<0.002mm
H2C	Brandvlei 2000	0-20	0.18	1.87	15.95	17.62	15.67	17	13.65	7.2	3.02	9.56
H2C	Brandvlei 2001	40-60	0.34	1.89	21.07	18.98	13.95	15.93	11.54	6.7	2.32	9.29
H2C	Brandvlei 2002	80-100	0.2	1.98	14.07	19.48	17.25	17.41	12.67	7.36	2.43	8.97
H2E	Augrabies 2110	0-20	-0.22	1.88	6.62	12.01	13.15	16.49	18.27	8.88	10.84	12.95
H2E	Augrabies 2111	40-60	-0.16	1.87	7.7	12.41	13.47	16.81	16.44	7.27	9.24	16.19
H2E	Augrabies 2112	80-100	-0.15	1.78	7.34	10.9	11.08	12.83	15.57	14.96	14.05	12.66
H2O	Oudtshoorn 2110	0-20	-0.26	2.25	7.53	16.7	16.44	32.88	7.95	4.83	1.89	11.25
H2O	Oudtshoorn 2111	40-60	-0.11	1.78	8.32	13.5	12.49	15.22	16.93	8.26	7.18	17.54
H2O	Oudtshoorn 2112	80-100	-0.26	1.78	8.94	12.43	11.01	17.09	20.72	8.42	6.3	14.68
H4C	Augrabies 1110	0-20	-0.04	1.99	11.29	16.6	16.65	23.48	11.01	6.27	2.57	11.94
H4C	Augrabies 1110	40-60	0.31	2.06	18.96	20.36	17.95	17.03	8.31	4.26	1.89	11.04
H4C	Augrabies 1110	80-100	-0.07	1.97	6.82	12.88	14.41	16.64	12.73	8.02	11.24	17.16
H4E	Augrabies 1110	0-20	-0.1	1.95	7.98	13.9	15.03	19.05	14.12	8.26	5.81	15.73
H4E	Augrabies 1110	40-60	-0.14	2.1	7.49	16.46	15.53	26.5	11.13	5.41	2.42	14.32
H4E	Augrabies 1110	80-100	-0.14	1.93	8.34	13	14.55	18.82	14.92	7.88	6.35	15.94
H4O	Valsrivier 2221	0-20	-0.2	1.97	6.31	12.84	14.52	19.35	16.79	8.75	5.54	15.81
H4O	Valsrivier 2222	40-60	-0.23	1.92	5.74	11.94	12.71	17.06	17.26	14.34	2.91	17.83
H4O	Valsrivier 2223	80-100	-0.1	1.86	6.04	9.87	10.44	12.25	11.67	10.35	12.67	26.57

a)



b)

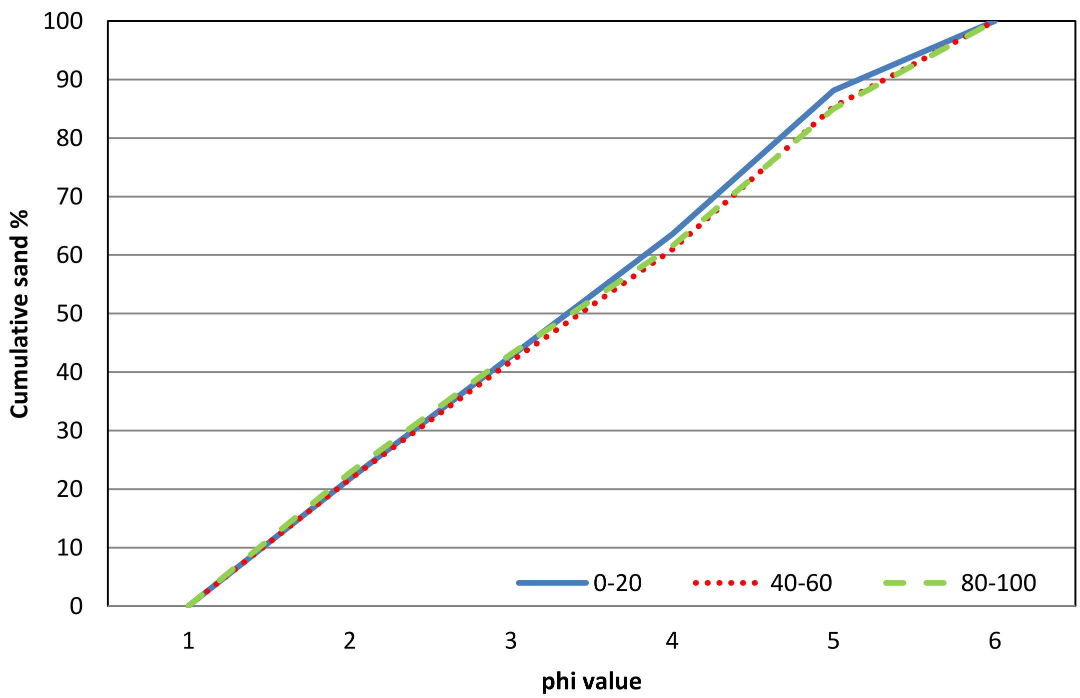


Figure 3.17: Degree of mixing of the sand fractions by indicating cumulative sand percentages in different soil depths in a) heuweltjie soil in comparison to b) non-heuweltjie soil in the Robertson study area. The size of the sieves (in mm) used for sand fraction separation is converted via the logarithmic scale and is shown here as the phi value.

3.1.3 Soil water content

3.1.3.1 Stellenbosch

In both the heuweltjie and non-heuweltjie soils, the same trend can be followed for soil water content over the seven trial months (November to May). Over the course of the first four months a decrease was noticed with every measurement as rainfall and irrigation was lower than the combined ET and plant-water-use, where after an increase in soil water content occured in March as irrigation was applied and higher rainfall was observed. In April a slight decrease was again observed, preceding a distinct increase due to very high rainfall in May (Table 3.7).

When an actual comparison is drawn between the soil water content of heuweltjie and non-heuweltjie soils, a clear distinction can be made between the two. The average total water content of heuweltjie soils ranged from 61.8 mm in February to 179.4 mm in May, while non-heuweltjie soils exhibited values that ranged from 55.8 mm in February to 165 mm in May. When compared statistically, a difference was noted between the heuweltjie and non-heuweltjies in θv in November and December ($p < 0.05$); differences in depth were also significant. These differences seem to become less prominent as the season progress and rainfall increase in autumn. The ET values are also indicative of the advantage that the heuweltjies have over the non-heuweltjies in terms of soil water content, in the Stellenbosch study area. On the heuweltjie, average ET values ranged from 0.4 mm/day in April to 2.1 mm/day in December. In comparison, the ET values on the non-heuweltjie plots ranged from 0.6 mm/day from April to 1.9 mm/day in January. The average ET per day was higher on the heuweltjie than the non-heuweltjie areas up and till April, where after values exhibited opposite trends.

3.1.3.2 Robertson

Opposite trends to that of Stellenbosch are observed when the heuweltjie and non-heuweltjie soil water contents are compared over the course over the seven trial months. In the heuweltjie soils, an increase was noticed from November to December, where after it decreased up and to February. A slight increase was then noted in March, where it decreased again in April. May brought an increase in soil water content due to high rainfall. In the non-heuweltjie soils a decrease-increase pattern was observed from November up and to March, where after another increase was discerned in April. May brought about a decrease in soil water content.

The average total water content of the heuweltjie soils in the Robertson study area ranged from 46.8 mm in February to 60.8 mm in May, while it ranged from 60.4 mm in February to 73.2 mm in April in the non-heuweltjie soil, thus clearly depicting a lower soil water content on the heuweltjies when compared to non-heuweltjie plots (Table 3.8). Statistically, differences in soil water content between the heuweltjie and non-heuweltjie plots were significant in the months of November, January and March, at depths of 80-100 cm ($p < 0.05$), with the non-heuweltjie plots displaying higher values. In November, the non-heuweljtie plots at the 50-80 cm depth also exhibited significantly higher soil water content than the heuweltjie plots. Through examination of the ET values, it is once again clear that the heuweltjies displayed lower soil water contents than corresponding non-heuweltjie areas. On the heuweltjie, values ranged from 2.3 mm/day in May to 5.1 mm/day in March, while the non-heuweltjie plots exhibited values ranging from 2.9 mm/day in May to 5.1 mm/day in March. No pattern could be discerned between the ET values of the heuweltjie -and non-heuweltjie plots.

Table 3.7: Average volumetric soil water contents of heuweltjie and non-heuweltjie plots in the Stellenbosch study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (ET) that occurred from that plots.

	Heuweltjie soil water content (mm)							
	Date	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Depth (cm)	0-30	43.9	25	16.5	13.7	22.3	19.1	46.7
	30-50	41	27.9	18.6	13.5	19	19.2	41.6
	50-80	40.6	32	21.6	15.2	19.4	19.9	42.7
	80-100	47.9	41.8	24.1	19.4	23.7	23.8	43.9
	Total	173.3	126.6	80.8	61.8	84.4	82	174.9
	Difference	-	46.7	45.9	19	-22.6	2.4	-93
	Rainfall (mm)	-	0.25	7.87	0.51	37.07	10.41	141.97
	Irrigation (mm)	-	0	0	13.8	24.8	0	0
	ET (mm)	-	46.9	53.8	33.3	39.2	12.8	49
	ET/day (mm)	-	2.1	2	1.3	1.5	0.4	1.4
	Non-heuweltjie soil water content (mm)							
	Date	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Depth (cm)	0-30	35.9	22.4	16	11.7	20.1	16.4	42.4
	30-50	34.9	24.9	14.6	10	18.8	15.9	36.1
	50-80	37.9	30	17.5	13.9	20.8	19.1	41.7
	80-100	45.3	38.8	25.1	20.2	25.6	23.7	44.8
	Total	153.9	116	73.1	55.8	85.3	75.1	165
	Difference	-	37.9	42.9	17.4	-29.5	10.2	-90
	Rainfall (mm)	-	0.25	7.87	0.51	37.07	10.41	141.97
	Irrigation (mm)	-	0	0	13.8	24.8	0	0
	ET (mm)	-	38.1	50.7	31.6	32.3	20.6	52
	ET/day (mm)	-	1.7	1.9	1.2	1.2	0.6	1.5

Table 3.8: Average volumetric soil water contents of heuweltjie and non-heuweltjie plots in the Robertson study area over the course of seven months (November 2009 to May 2010), as well as the evapotranspiration (ET) that occurred from that plots.

Heuweltjie soil water content (mm)								
	Date	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Depth (cm)	0-30	13.7	18.7	16	17.1	17.8	14.3	17.2
	30-50	11.4	14	12.8	11.8	13.8	13.1	14.8
	50-80	11.3	11.3	11.4	9.2	12.2	12.6	14
	80-100	14.5	12.3	12	8.7	11.7	13.9	14.8
	Total	51	56.3	52.2	46.8	55.6	53.8	60.8
	Difference	-	-5.3	4.1	5.4	-8.8	1.8	-7
	Rainfall	-	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	-	100	108.4	113.5	103.4	100	60
	ET	-	100.1	121.5	123.5	138.4	113.6	56.9
	ET/day	-	4.4	4.3	4.3	5.1	3.2	2.3
Non-heuweltjie soil water content (mm)								
	Date	**November**	**December**	**January**	**February**	**March**	**April**	**May**
Depth (cm)	0-30	14.9	17.3	15.9	15.7	19.5	17.7	16.6
	30-50	14.4	15.1	15.4	15.4	16.8	16.6	15
	50-80	16.3	14.5	16.8	14	17	18.2	15.7
	80-100	18.7	17.4	18.6	15.4	17.9	20.6	17.3
	Total	64.3	64.2	66.7	60.4	71.2	73.2	64.5
	Difference	-	0.1	-2.5	6.2	-10.7	-2	8.7
	Rainfall	-	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	-	100	108.4	113.5	103.4	100	60
	ET	-	105.5	114.9	124.3	136.5	109.8	72.6
	ET/day	-	4.6	4.1	4.3	5.1	3	2.9

2.2 Chemical properties

3.2.1 pH

3.2.1.1 Stellenbosch

The pH (KCl) values obtained, range from 4.58 in the 80-100cm sample of H3On to 6.89 in the 40-60 cm sample of H1Os, with the highest average value being exhibited by the Crest plots, with a pH of 5.81. HOn exhibited the lowest total average, with a pH of 5.54. Although outlier values do occur in the high pH range of the non-heuweltjie plots, the highest average pH values occurs on the HC plots (as shown in Figure 3.18). These values indicate that the soils are acidic and could induce some nutrient deficiencies and toxicities. This statement will be further clarified in the discussion of this section.

When the average pH values per depth are examined, it is clear that any differences that might occur are insignificant and values are very similar on and off the heuweltjie. The average pH values of the HC plot, range from 5.66 in the 80-100 cm sample to 5.97 in the 20-40 cm sample; HO plots between 5.36 in the 80-100 cm sample to 5.99 in the 20-40 sample, and HE plots between 5.2 in the 80-100 cm sample to 5.94 in the 0-20 cm sample. The pH values of the HEn plots were higher than that of the respective HEs plots, while the opposite was discerned for the Off-plots, with HOs displaying higher values than HOn. The pH of the heuweltjie plots are fractionally higher than corresponding non-heuweltjie plots, however due to the high degree of leaching of basic cations any differences are small and no particular conclusion can be derived by just taking the pH values into account. Differences between heuweltjie and non-heuweltjie plots on the same depth were all insignificant ($p > 0.05$).

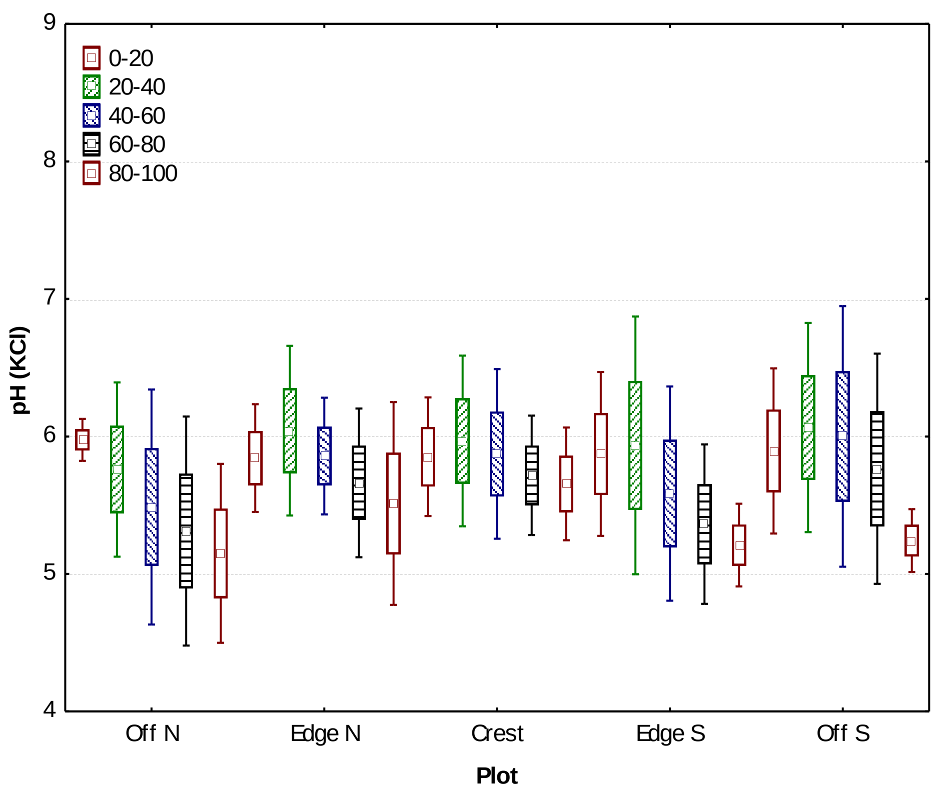


Figure 3.18: Average pH values on the different plots on and off the heuweltjie in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.1.2 Robertson

The pH (KCl) values range from 4.00 in the 80-100 cm of the H4O plot to 8.74 in the 80-100 cm of H1C. The highest plot average is exhibited by HE, with a pH of 8.19. The lowest average was exhibited by HO, with a pH of 7.2 (as shown in Figure 3.19). The pH values obtained from all the soil samples of H4O exhibit strong acidic tendencies, which is peculiar given that the values are generally above 7.

Average pH values per depth emphasize the above mentioned conclusions. The values of the HC plot range from 7.97 in the 0-20 cm sample to 8.3 in the 80-100 cm sample; HO plot between 7.43 in the 40-60 cm sample to 7.96 in the 0-20 cm sample, and HE plot displaying values ranging from 8.07 in the 0-20 cm sample to 8.3 in the 80-100 cm sample. The same observation was made as for that in the Stellenbosch study area, with heuweltjie plots exhibiting higher overall pH values than non-heuweltjie soils. Only in this case, the HE plots displayed higher values than the HC plots. Differences were insignificant though ($p > 0.05$). Significant differences ($p < 0.05$) were observed between the HC and HO, as well as between HO and HE plots in the 60-80 cm and 80-100 cm plots. By examining these results it is apparent that a significant difference exists in the overall average pH values of the heuweltjie and non-heuweltjie plots.

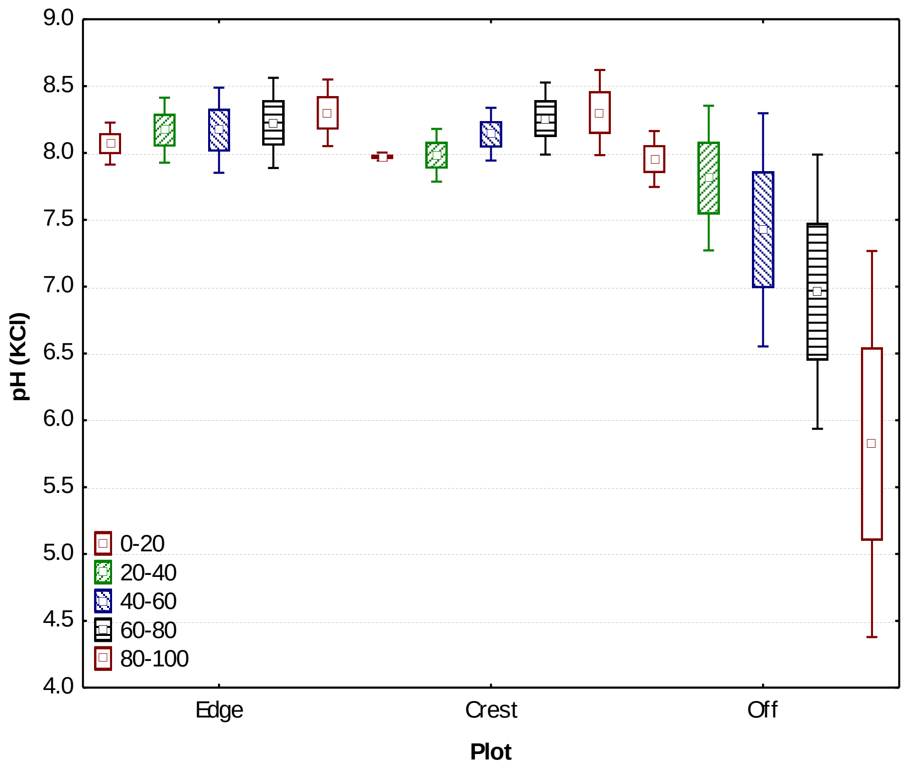


Figure 3.19: Average pH values on the different plots on and off the heuweltjie in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.2 Electrical Conductivity

The log values of the EC_e were taken so that some sort of comparison could be drawn between the values found in the Stellenbosch and Robertson study areas.

3.2.2.1 Stellenbosch

A very small variation can be noticed when comparing the values on the heuweltjie to those off the heuweltjie. The crests of the heuweltjies have lower EC_e value than its edges and adjacent surrounding soils, with average EC_e values of the HC plot range from 51.80 mS/m in the 60-80 cm sample to 66.38 mS/m in the 0-20 cm sample; HOn from 65.85 mS/m in the 0-20 cm sample to 90.30 mS/m in the 80-100 cm sample; HOs from 64.58 mS/m in the 20-40 cm sample to 98.80 mS/m in the 0-20 cm sample; HEn from 56.60 mS/m in the 20-40 cm sample to 78.90 mS/m in the 80-100 cm sample, and HEs ranging from 66.78 mS/m in the 0-20 cm sample to 96.48 mS/m in the 80-100 cm sample (Figure 3.20). These higher values of the HO and HE plots in comparison to the HC plots, could be due to the concave shape of the heuweltjies, as Na that makes up the highest percentage of the salt concentration that influences the EC_e value, is very mobile and tends to move to the edges of the heuweltjie as well as its adjacent soil (F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication). However, differences between HC, HE and HO plots were very small and insignificant ($p > 0.05$).

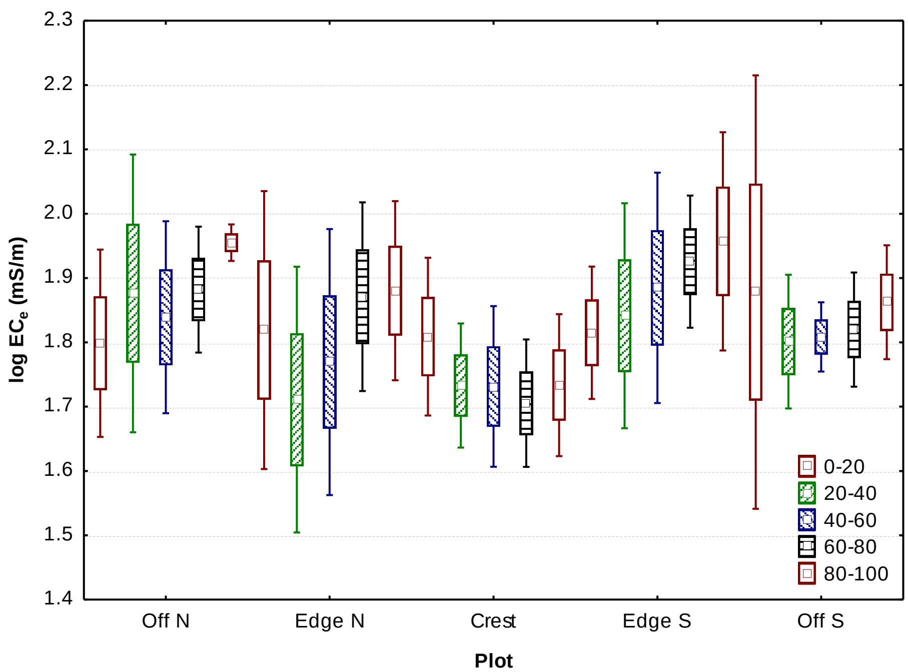


Figure 3.20: Average EC_e values per depth on the different plots on and off the heuweltjie in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. The log values were used so that comparisons could be made between Stellenbosch and Robertson. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.2.2 Robertson

On average, EC_e displayed the highest values in the topsoil, after which it decreased up to 60 cm, only to lead to another increase up to 100 cm. This trend can be followed for all the sampling plots. Values were high in the H2O plot, which indicated high concentrations of Na, as shown in the exchangeable cation analysis. It shows a definite increase in Na content in the 80-100 cm sample of the H2O plot, with the Na content being almost three times higher than the closest value (except for H4O which is also quite high). The exchangeable sodium percentage (ESP) of H2O's 80-100 cm sample is 20%, which provide favourable conditions for the formation of a dorbank (Remnants of a dorbank still present in this specific soil profile).

Average EC_e values of the HC plot range from 253.50 mS/m in the 60-80 cm sample to 315.25 mS/m in the 80-100 cm sample; HO plot from 320.25 mS/m in the 40-60 cm sample to 515.75 mS/m in the 0-20 cm sample, and HE plot from 190.38 mS/m in the 60-80 cm sample to 361.25 mS/m in the 0-20 cm sample. The EC_e values correlate reasonably well with the pH, except in the case of H4O, where the high EC_e value of does not associate with the low pH of 5.42. H4O is of the Valsrivier soil type and its 80-100 cm sample displays a clay percentage of 27%, the highest of all the soils sampled in the study area.

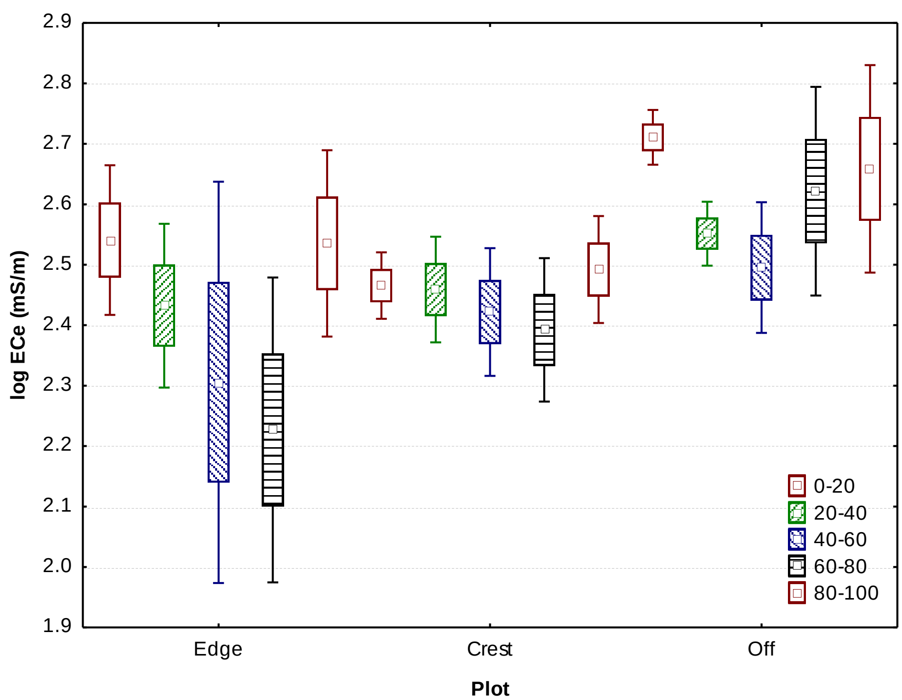


Figure 3.21: Average EC_e values per depth on the different plots on and off the heuweltjie in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. The log values were used so that comparisons could be made between Stellenbosch and Robertson. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

The EC_e varies considerably between HC and HO plots, as well as between HO and HE plots at all depths, with values ranging from 99.5 mS/m in the 60-80cm plot on H2E, to 679 mS/m in the 80-100 cm sample on H2O. Statistically, significantly higher values were observed on the HO plots than both HC and HE plots ($p < 0.05$). Insignificant differences were however found between HC and HE.

Above mentioned results indicate possible implications for grapevine. This is explained by Saayman in Table 3.9.

Table 3.9: Interpretation of results obtained from a saturated paste extract of a heuweltjie and non-heuweltjie plot (H2) in the Robertson study area according to the index of Saayman (1981).

Site	Depth (cm)	Rating	EC_e (mS/m)	Effect on the plant*
Crest	0-20	Slightly saline	325	2
	20-40	Slightly saline	324	2
	40-60	Slightly saline	309	2
	60-80	Slightly saline	306	2
	80-100	Slightly saline	324	2
Edge	0-20	Slightly saline	327	2
	20-40	Non saline	187.3	1
	40-60	Non saline	103	1
	60-80	Non saline	95.5	1
	80-100	Slightly saline	285	2
Off	0-20	Moderately saline	573	3
	20-40	Moderately saline	421	3
	40-60	Moderately saline	426	3
	60-80	Moderately saline	633	3
	80-100	Moderately saline	679	3

*1 - Salinity effects mostly negligible

*2 - Yields of sensitive crops affected

*3 - Yields of many crops affected

3.2.3 Exchangeable cations

Where statistics is explained in terms of significant differences and p-values, the superior variable with higher value will be indicated with a (+), while the inferior variable with lower value is indicated with a (–). The plot averages of the respective cations were used to draw up the graph as it was found to portray a much clearer picture than when all the specific depths were included.

3.2.3.1 Stellenbosch

By examining Figure 3.22, it is apparent that the chemistry of the soils, both on and off the heuweltjie, is dominated by Ca. Even while Ca does not occur in high concentrations, it still eclipses the next highest value which is Mg, by an average of 55%. A very small increase is observed in the Ca and Mg values of the heuweltjies when compared to the surrounding soils. When the K values on and off the heuweltjies are compared, a different trend prevails. Higher values were detected on the Off-plots than on the heuweltjie plots. However, Na and K values are too low for any substantial conclusion to be drawn from the results and no clear distinction can be made between the heuweltjie and non-heuweltjie plots.

For Ca, variations between plots were found in all depths. In the 0-20 cm sample, significant differences ($p < 0.05$) were observed between HC(+) and HEn(-), as well as HC(+) and HOn(-); in the 40-60 cm sample significant differences were observed between HC(+) and HEn(-), HC(+) and HOn(-), HEn(-) and HOs(+), HOn(-) and HOs(+), as well as HOn(-) and HEs(+); and in the 80-100 cm sample significant differences were found between HC(+) and HEn(-), HC(+) and HOn(-), HC(+) and HOs(-), as well as between HC(+) and HEs(-). The average Ca value over all depths for the HC plots was 5.16 cmol/kg; HOn 3.44 cmol/kg; HOs 4.53; HEn 3.74 cmol/kg and HEs 3.99 cmol/kg. Thus, the overall conclusion was that Ca is present in higher concentrations on the heuweltjie soils compared to the non-heuweltjie soils.

For Mg, variations were less distinctive in the 0-20 cm sample, but differences were found between heuweltjie and non-heuweltjie plots in the subsoil. Significant differences were observed between HC(+) and HEn(-), HC(+) and HOn(+), as well as HC(+) and HOs(-) plots for both the 40-60 and 80-100 cm samples ($p < 0.05$). The average Mg value over all depths for the HC plots was 1.27 cmol/kg; HOn 0.69 cmol/kg; HOs 0.78; HEn 0.80 cmol/kg and HEs 0.80 cmol/kg. Although values were extremely low, heuweltjie plots still exhibited higher Mg concentrations in comparison with the non-heuweltjie soils.

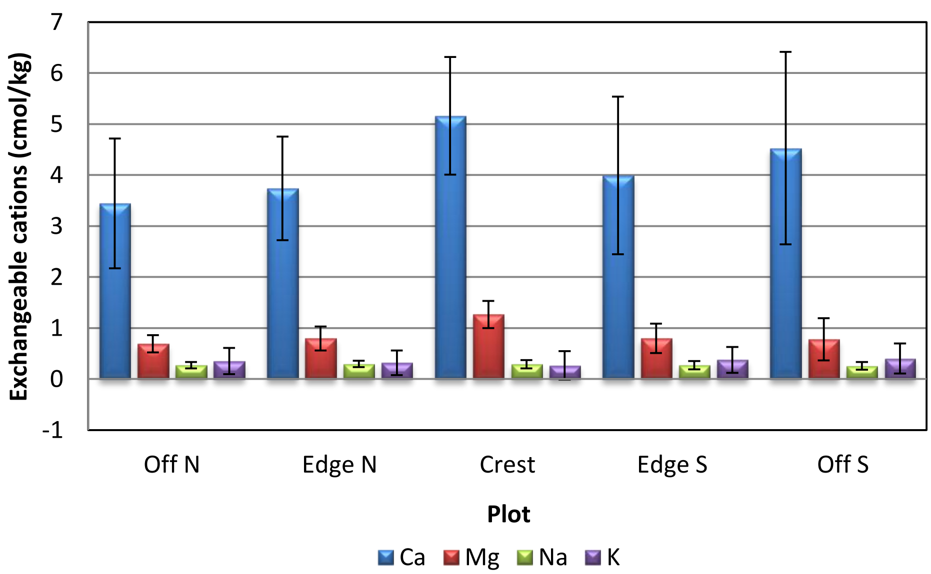


Figure 3.22: Exchangeable cation values on the different plots on and off the heuweltjie in the Stellenbosch study area. Standard deviation bars are indicated. Statistical comparisons were made at one depth only, between heuweltjie

and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

There were no significant differences between heuweltjie and non-heuweltjie plots concerning Na. The average Na value over all depths for the HC plot was 0.29 cmol/kg; HOn 0.27 cmol/kg; HOs 0.26; HEn 0.30 cmol/kg and HEs 0.27 cmol/kg. The heuweltjie plots exhibited lower K values than non-heuweltjie plots, in all depths. The average K value over all depths for the HC plots was 0.27 cmol/kg; HOn 0.35 cmol/kg; HOs 0.40; HEn 0.32 cmol/kg and HEs 0.37 cmol/kg. This time round the non-heuweltjie plots seem to exhibit higher values than the heuweltjie plots. The only significant differences ($p < 0.05$) however, were found between the 40-60 and 80-100 cm samples of HC(-) and HOs(+).

3.2.3.2 Robertson

As in the case of the Stellenbosch study site, the exchangeable cations are dominated by Ca, with K being a distant second, averaging almost 45% lower. In general Na occurs in the soils in very low quantities, except for the 80-100 cm sample of the H2O plot, where Na makes up 20% of the total exchangeable cation percentage (Figure 3.23). This was found to correlate well with the corresponding ECe values, which is a good indication of soil salinity.

When the exchangeable cation values of the heuweltjie plots are compared to the non-heuweltjie plots in the surrounding soils, a slight increase can be observed, except in the case of Na. The Ca value of the HC plots averages approximately 2 cmol/kg higher than the corresponding values on the HE plots, which in turn averages 4 cmol/kg higher than the HO plots. The average Ca value over all depths for the HC plots was 12.22 cmol/kg; HO 8.38 cmol/kg and HE 10.34 cmol/kg.

For Mg, the HE plots displayed the highest values, followed by HC and HO. The average Mg value over all depths for the HC plots was 1.52 cmol/kg; HO 1.20 cmol/kg and HE 2.08 cmol/kg. The Na values exhibited a different trend, with HO plots displaying the highest values, followed by HE and HC. The average Na value over all depths for the HC plots was 0.62 cmol/kg; HO 0.87 cmol/kg and HE 0.69 cmol/kg. The average K values were almost identical in all the plots with HC plots 2.50 cmol/kg; HO 2.28 cmol/kg and HE 2.64 cmol/kg.

Differences in the exchangeable cation contents between heuweltjie and non-heuweltjie plots were small and striking differences were hard to find. Significant differences ($p < 0.05$) in the Ca content did however occur in the 40-60 and 80-100 cm samples, between the HC(+) and HO(-) plots. For Mg, significant differences were observed in the 40-60 cm sample, between HC(+) and HO(-), and in the 80-100 cm sample, between HC(-) and HE(+), as well as between HO(-) and HE(+). Only one significant difference was observed in the Na content between the heuweltjie and non-heuweltjie plots, occurring in the 80-100 cm sample, between HC(-) and HO(+). Heuweltjie and non-heuweltjie plots displayed insignificant differences in K content at all depths ($p > 0.05$).

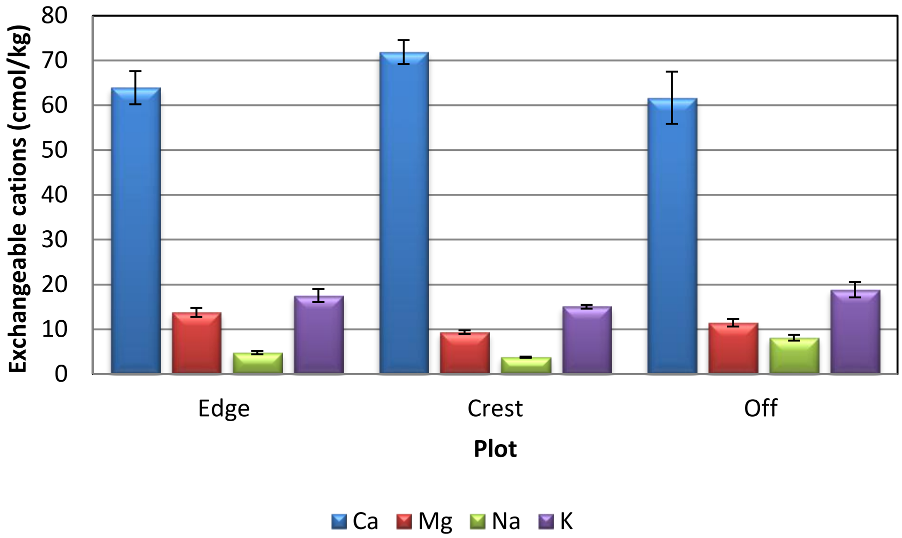


Figure 3.23: Exchangeable cation values on the different plots on and off the heuweltjie in the Robertson study area. Standard deviation bars are indicated. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.4 Extractable Phosphorus

<u>3.2.4.1 Stellenbosch</u>

The highest average P content was found on the non-heuweltjie plots. The values decreased on HE and further decreased on HC (Figure 3.24). When the topsoil and subsoil were compared, the 0-20 cm samples displayed the highest P values. The average P value over all depths for the HC plots was 10.32 mg/kg; HOn 19.48 mg/kg; HOs 12.37 mg/kg; HEn 10.29 and HOs 10.92 mg/kg. P values ranged from 4.10 mg/kg, detected in the 80-100 cm sample of both H1Os and H2Os, to 38.70 mg/kg, detected in the 40-60 cm sample on H1On. No significant differences were found between heuweltjie and non-heuweltjie plots at any of the depths ($p > 0.05$).

<u>3.2.4.2 Robertson</u>

A much higher average P content was found in the soils of the Robertson study area, with values ranging from 2.00 mg/kg in the 80-100 cm sample of H4O, to 208.01 mg/kg in the 0-20 cm sample of H4E. The values more or less follow the same trend as the Stellenbosch values, with regards to the topsoil and subsoil concentrations. However, the highest average P content was observed in the Edge plots, where after values decreased on the Crest and Off-plots (Figure 3.25). The average P value over all depths for the HC plots was 47 mg/kg; HO 44 mg/kg and HE 73.11 mg/kg. P values ranged from 2 mg/kg in the 80-100 cm sample of H4O, to 208.10 mg/kg in the 0-20 cm sample of H4E. No significant differences were found between heuweltjie and non-heuweltjie plots at any of the depths ($p > 0.05$).

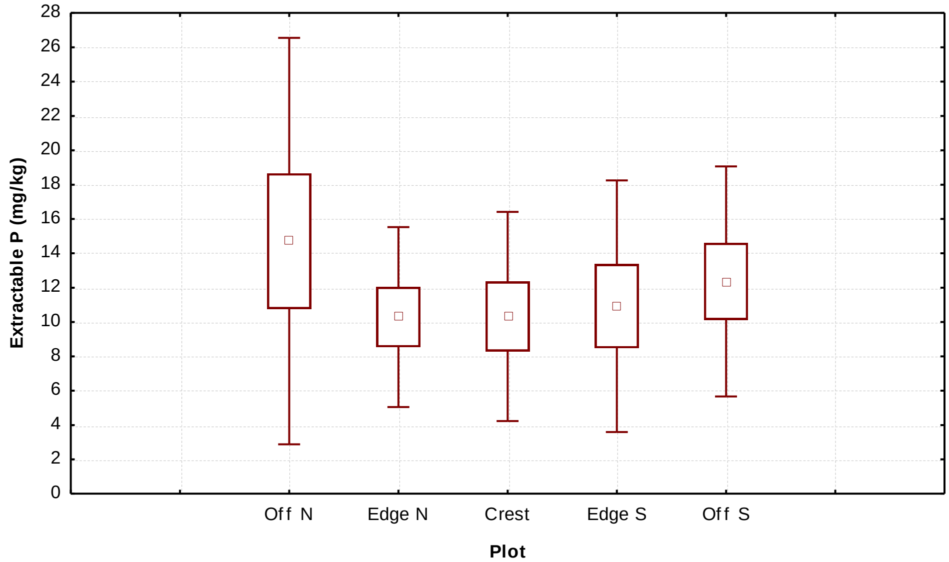


Figure 3.24: Extractable phosphorous values on the different plots on and off the heuweltjie in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD pothoc test.

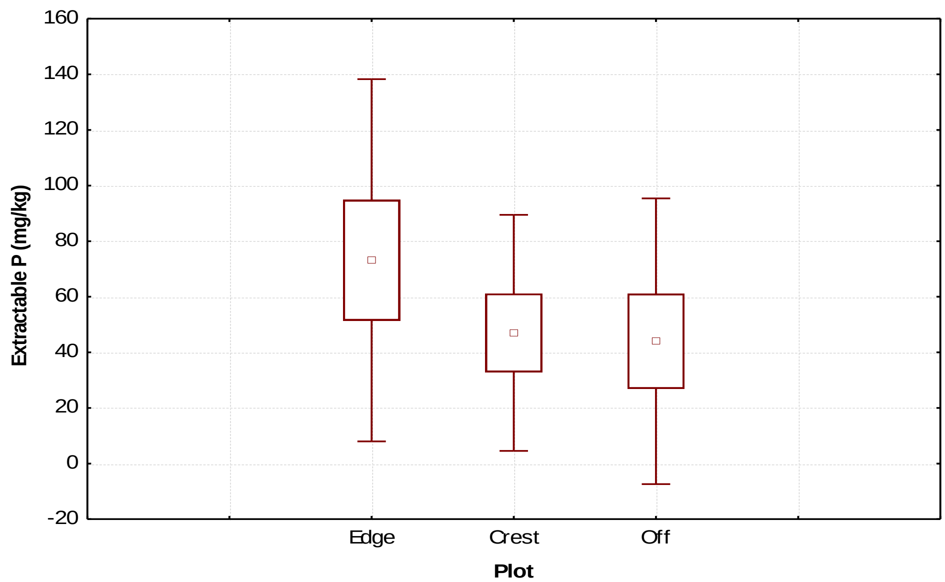


Figure 3.25: Extractable phosphorous values on the different plots on and off the heuweltjie in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.5 Total carbon and nitrogen

3.2.5.1 Stellenbosch

A higher total C and N percentage were observed in the top 20 cm of all the plots and can be ascribed to the accumulation and decomposition of plant litter and detritus on the soil surface. Results also showed that a decline in C and N percentages takes place with increase in depth. The average total C percentage over all depths for the HC plots was 1.22 %; HOn 0.92 %; HOs 0.98 %; HEn 0.93 % and HEs 0.98 %; while the average total N percentage over all depths for HC plots were 0.09 %; HOn 0.07 %; HOs 0.06 %; HEn 0.05 % and HEs 0.09 % (Figure 3.26). The C values ranged from 0.44% in the 80-100 samples of both H1Es and H4En, to 1.68% in the 0-20 cm sample on H4C; while the N values ranged from BD (below detection) in the 80-100 cm sample on H4En to 0.21% in the 0-20 sample on H1Es. The total C and N percentage of the Crest plots were significantly higher when compared to the values of the Edge and Off-plots at the same depths. Differences in the C and N values between the Edge and Off-plots were negligible. Significant differences between heuweltjie and non-heuweltjie total C contents were found in the 0-20 cm sample, between HC and HO, and in the 80-100 cm between HC and HO, as well as between HC and HE ($p < 0.05$). Differences in total N content proved insignificant ($p > 0.05$).

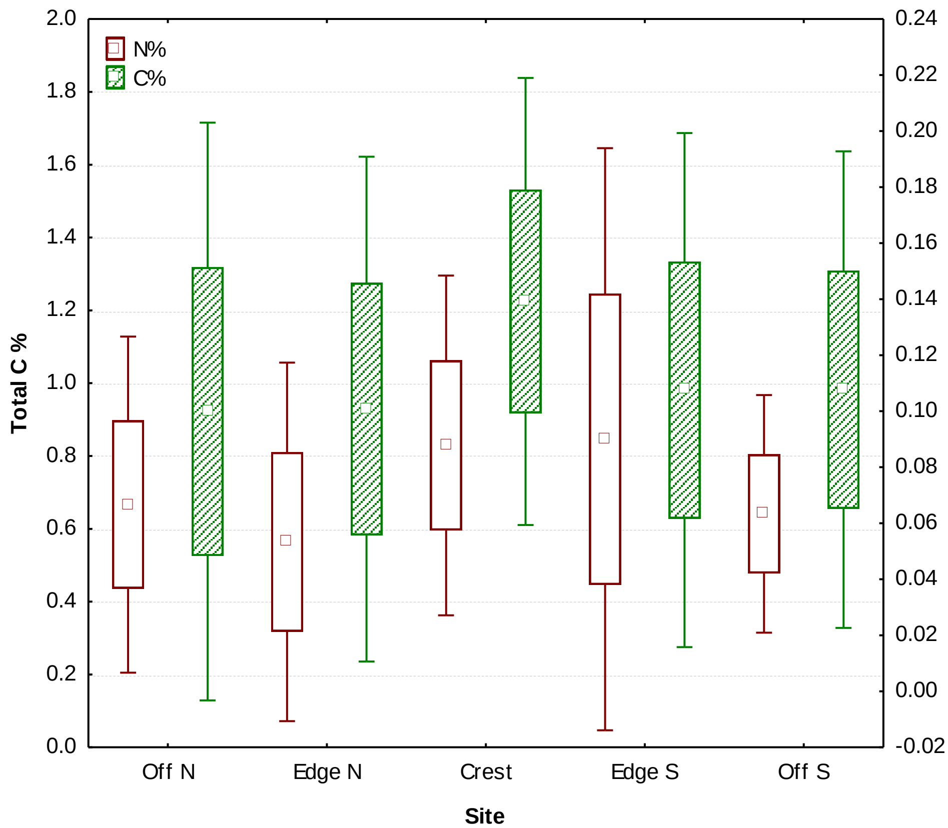


Figure 3.26: Total carbon and nitrogen percentages on different plots on and off the heuweltjie in the Stellenbosch study are factorial. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and

not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.5.2 Robertson

The general trend of the C and N values is one that decreases with depth - the reason for this was already explained. The total C percentage of the 0-20 cm plots is the highest on the HC plot where after it decreases in both the HE and HO plots. The results of the samples in the 40-60 cm plots exhibit a different pattern, with the HE plots showing the highest C values. On average, the lowest values are observed on the HO plots. No correlation can be drawn from the N values of the HE and HO plots. The average total C percentage over all depths for the HC plots was 0.99 %; HO 0.67 % and HE 0.95 %; while the average total N percentage over all depths for HC plots were 0.05 %; HO 0.05 % and HE 0.06 %. The highest C value was 2.22%, detected in the 0-20 cm sample of H4C, with the lowest being 0.16% in the 80-100 cm sample of H3E. The N values ranges from BD in the 40-60 cm sample of both the H3E and H3O plots as well as the 80-100 sample of H3O, to 0.12% detected in the 40-60 and 80-100 cm samples of H4E. Differences between heuweltjie and non-heuweltjie total C and N contents were insignificant at all depths ($p > 0.05$).

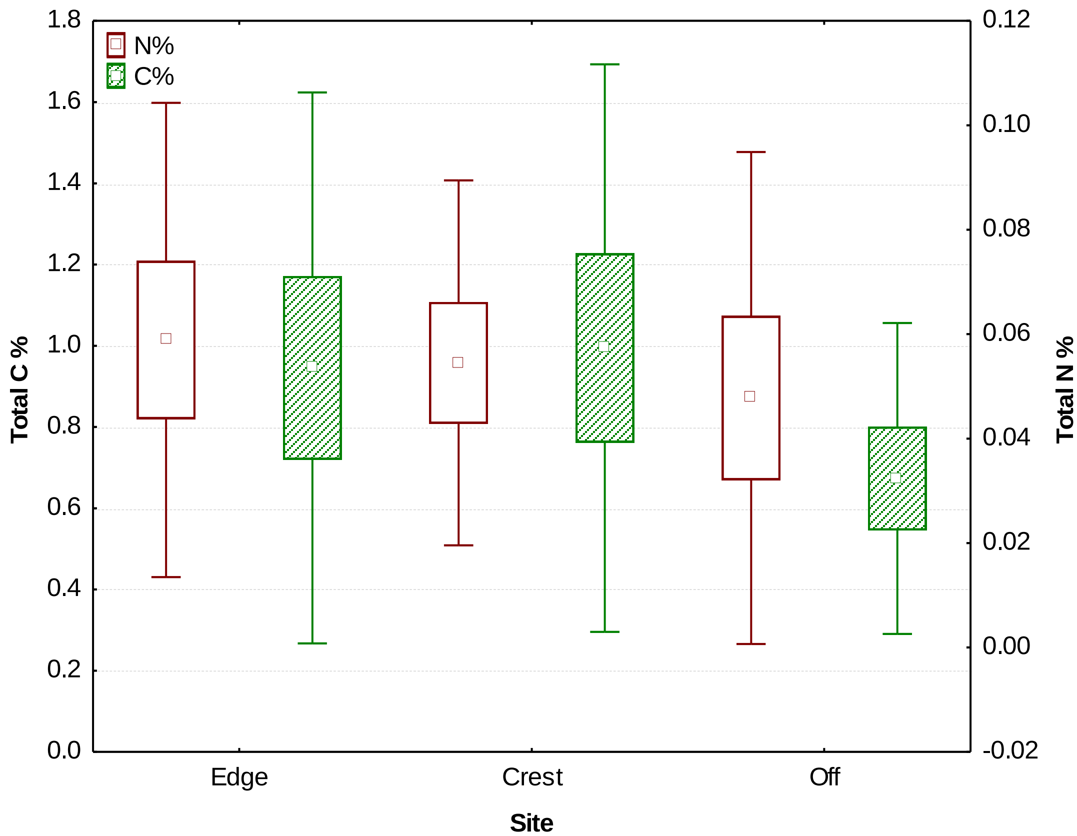


Figure 3.27: Total carbon and nitrogen percentages on different plots on and off the heuweltjie in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. Statistical comparisons were made at one depth only, between heuweltjie and non-heuweltjie areas and not across different depths. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test. n=4.

3.2.6 Organic carbon

Only one heuweltjie at each study area (H4) was examined for the purposes of organic carbon content due to financial constraints. This experiment was done to supplement the total carbon results, to get an indication of the fraction of total carbon occupied by organic carbon and to get an indication of changes with depth.

<u>3.2.6.1 Stellenbosch</u>

The organic carbon values follow a similar trend to that of the total carbon values, and decreases with depth as well as from Crest to Edge and Off-plots. However the difference in the values of the Edge and Off-plots are much more significant, with the Edge plots clearly exhibiting higher values. The average organic C percentage over all depths for the HC plot was 1.31 %; HO 0.97 % and HE 1.09 % (Figure 3.28).

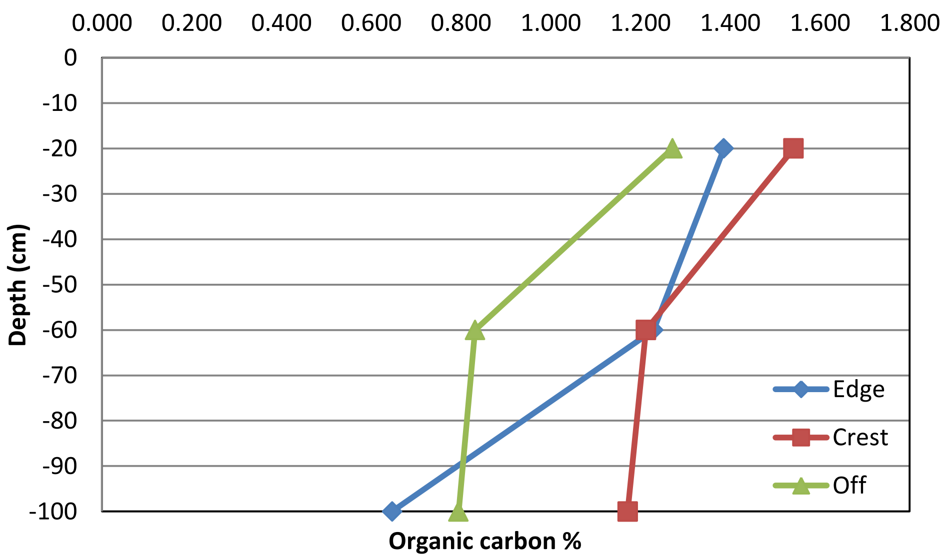


Figure: **3.28:** Organic carbon percentages on different plots on and off the heuweltjie in the Stellenbosch study area.

<u>3.2.6.2 Robertson</u>

The organic carbon values do not follow any particular trend and values seem to be highest on the Edge plot while it declines on the Off plot. The lowest values are observed on the Crest plot. A very high organic carbon value is observed in both the 40-60 cm and 80-100 cm of the H4E plot and has a major influence on the results. Due to the fact that only one heuweltjie was sampled, a cause for this anomaly could not be statistically clarified and the reason for the high H4E organic calues could simply be an accumulation of organic matter at that specific location. The average organic C percentage over all depths for the HC plots was 0.49 %; HO 0.72 % and HE 1.27 % (Figure 3.29).

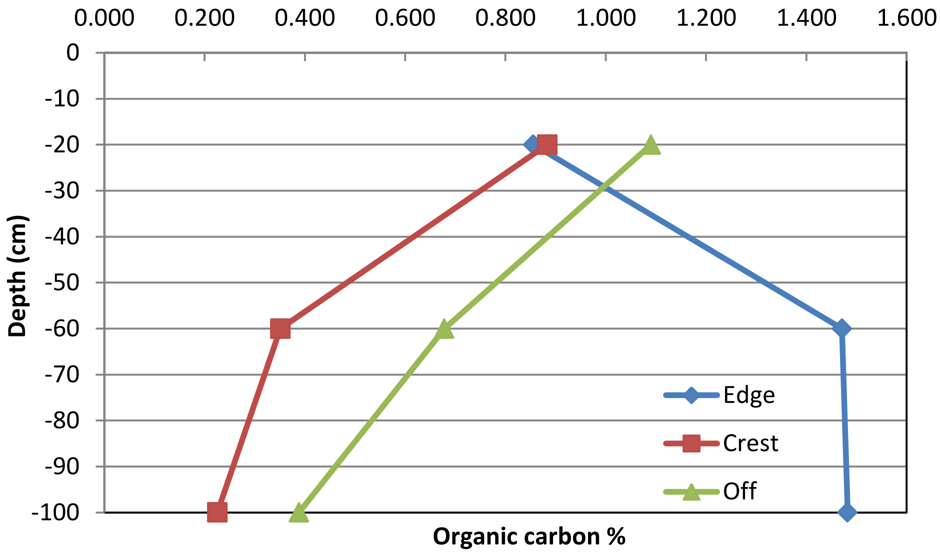


Figure 3.29: Organic carbon percentages on different plots on and off the heuweltjie in the Robertson study area.

4. DISCUSSION

Soil properties can be considerably altered by termite activity through either mound-building, gallery excavating activities or modes of feeding (Bignell and Holt, 2002). The significance of these alterations lies in their abundance and biomass as well as their distinctive affiliation with a huge variety of microorganisms. Termites are beneficial for plant growth in that they advance organic matter decomposition and nutrient cycling, as well as reduce erosion through modification of the soil physical, chemical and biological processes (Bignell and Holt, 2002).

It is virtually impossible to define a termite mound according to just its soil properties. It is necessary to incorporate parameters such as past and present land use with environmental factors, such as rainfall, vegetation, soil type and depth to water table, if present. The type of vegetation that preceded the vineyards in both the Stellenbosch and Robertson study areas are very much indicative of the nutrients found in the heuweltjie soils.

4.1 Physical properties

4.1.1 Bulk density

In both the Stellenbosch and Robertson study area, there were no differences observed in bulk density between the heuweltjie and non-heuweltjie plots at any of the sample depths. This is most probably due to the influence of man, through ploughing and soil tillage practiced in the vineyard blocks that were sampled. Therefore in cultivated landscapes such as the Stellenbosch and Robertson study area, no conclusion can be derived from these values as very little differences exist between heuweltjies and non-heuweltjies in terms of bulk density.

However, past studies showed that termites form macropores, loosen the soil and change the soil structure by burrowing. This reduces bulk density while at the same it increases soil porosity (Mando, 1997). This strongly correlates with earlier results from Mando *et al.*, (1996) where an average of 7% greater porosity was found on termite mounds in comparison with surrounding soils. Internal flow of water is greatlyincreased by macropores which leads to a higher saturated hydraulic conductivity in termite mounds in comparison with surrounding soils (Mando, 1997). The higher soil organic matter levels originating from termite activity can also have a significant effect on modifying the bulk density. Organic matter tends to reduce bulk density (Arvidsson, 1998; Chan, 2002; Rivenshield and Bassuk, 2007).

Termites collect clay from other soil horizons and mix it with their faeces to build the walls of the tunnels and galleries in their nest. This phenomenon leads to a decrease of pore sizes due to the filling of the pores with their finer faeces and it was speculated that the density of the soils on the heuweltjie would be higher. However, this was not the case here. According to Pulleman *et al.* (2005), earthworm activity can also contribute to the formation of stable micro-aggregates that are enriched in finer particles and organic C.

The initial hypothesis was that the bulk density values on the heuweltjies will display a much more homogeneous pattern through the profile when compared to the non-heuweltjie plots. This is due to mixing of the sand and clay particles through burrowing and nest-building activities of the termites, thus nullifying the effect of natural clay distribution and lessivage.

4.1.2 Texture analysis

The higher clay content of the heuweltjie soils in the Stellenbosch study area can be attributed partly to the fact that the termites selectively transport clay particles from other horizons into their nest and combine it with faecal material to build their tunnels and gallery walls (López-Hernandez, 2001). Evidence of the natural soil forming process of clay illuviation is absent in the soil of the heuweltjies, due to bioturbation caused by the termites. Examination of the clay percentages in the Robertson study area, and comparison between the heuweltjie and non-heuweltjie plots, show an opposite trend to that found in Stellenbosch. A lower clay percentage is observed on the heuweltjie plots when compared to non-heuweltjie plots. This is due to a higher percentage of free lime making up the soil matrix in the heuweltjie, at the expense of clay. The reason for this being so will be discussed in a later section.

Based on the results obtained, it was concluded that a fair degree of mixing took place through bioturbation by the termites via their burrowing activity. Their burrowing action in the case of nest-building has a major effect on the mixing of soil particles through different depths and can cause differences in particle size distribution when compared to adjacent, surrounding soils. When the results of the two study sites are weighed against each other, it is very clear that a greater degree of mixing occurred in the heuweltjies of Robertson than the heuweltjies of Stellenbosch. The reason for this could quite simply be because of the fact that there is a much higher percentage of sand in the Robertson profiles, and therefore a higher chance of mixing exists due to the increase in sandy substrate. There is also a difference in the way and the extent of the mixing of the specific sand fractions between the two study areas.

Kang (1978) and Brouwer *et al.* (1991), found that sand and silt values was much lower in mound soils when compared to surrounding soils, with the clay content subsequently being much higher. Similar observations were made by Hulugalle and Ndi (1993) and again by Ekundayo and Aghatise (1997). The higher silt content of the surrounding soils is a very clear indication of preferential transport and incorporation of clay by termites in their nests, and explains the lower silt and sand particles in termite mounds. According to Lal (1988), this is a feature of all termite species.

According to Konaté *et al.*, (1999), soil on above-ground termite mounds exhibited a higher proportion of fine particles than adjacent soils. Soil rehandling by termites (i.e. selection and importation of finest soil particles from deep to upper soil horizons) was shown to be the main source of modification of soil texture on mounds (Lee and Wood, 1971a). The porosity of soils clods was higher on the mound than in control areas, particularly for the deeper layers studied.

A key shrinking/swelling capability was also observed in the mound occurring in clay-rich soils (Bruand and Prost, 1987; Tavares-Filho and Tessier, 1998). It is a significant increase in the amount of 2:1 clays in the mound soil through incorporation by termites that allows for this phenomenon (Jouquet *et al.*, 2004). This shrinking capacity could induce soil cracking on mounds and thus could increase the water infiltration rate in dry conditions, and the deeper percolation of water. This could also improve the spatial distribution of roots by the effects of cracks due to the wet-dry soil cycles (Konaté et al, 1999).

Shale-derived, fine-textured soils, common in the Little Karoo, are prone to higher infiltration levels on vegetated patches and heuweltjies, when compared with the surrounding bare soil (Midgley and Musil, 1992). Le Maitre *et al.*, (2007) concluded that when rainfall exceeds infiltration rates, a reallocation of water and waterborne material takes place downslope to the next heuweltjie or vegetation patch. When these heuweltjies however become devegetated, it will develop into localized depressions due to erosion of its friable and loose soils (Vlok *et al.*, 2005).

It can be concluded that termites play an intricate part in altering the soil texture at specific depths through their foraging and burrowing activities. Due to the extensive cultivation and soil tillage in both the Stellenbosch and Robertson study areas, much of these alterations have been nullified. Differences in the distribution of different textural classes between heuweltjie and non-heuweltjie soils do however occur and while it is small, it is relatively significant and paves the way for further alterations in the soil physical properties.

4.1.3 Soil water content

On average, the soil water content was higher on the heuweltjie plots than the non-heuweltjie plots in the Stellenbosch study area. This can be attributed to the higher clay content which gives rise to a higher total porosity and a stronger water holding capacity. Mando (1997) found that macropores created by termites were coated with clay which is confirmation that these pores conduct water flow. The heuweltjies also contain a higher percentage of organic material and organic carbon than surrounding soils, which absorbs water and increase the soil's water retention. According to Rawls *et al.* (2003), the relationship between the soil's water holding capacity and organic carbon content is influenced by proportions of textural components. They state that at low carbon contents, an increase in the soil organic carbon content will result in an increase in water retention only in coarse textured soils while the water retention will decrease in finer textured soils. Where the organic carbon content of the soil is already high, any further increase will result in an increase in water retention of all textures. Thus according to this study, the already high percentage of organic carbon found in the fine-textured heuweltjie soils will lead to a stronger water holding capacity.

The difference in soil water content on and off the heuweltjies proved to be the most significant soil factor influencing the growth and physiology of the grapevines. Through examination of the soil water content and the eventual ET on the different plots, it is apparent that heuweltjies in the Stellenbosch study area displayed higher soil water contents and therefore higher ET values than corresponding non-heuweltjie areas. Therefore it can be concluded that grapevines growing on heuweltjies in the Stellenbosch will be much less prone to stress induced by water deficiencies than the vines associated with non-heuweltjies. These higher soil water contents could significantly mitigate the effects of climate change and global warming on the plant in terms of a higher availability of soil water, and heuweltjies could thus provide specific, yet very beneficial heterogeneity to cultivated landscapes.

In the Robertson study area the opposite was discerned, with the heuweltjie soils exhibiting lower soil water contents than the non-heuweltjie soils. As previously stated this has a significant effect on the growth and physiology of the grapevines, however with results in Robertson being opposite to that of Stellenbosch, the hypothesis was made that growth would be less vigorous on the heuweltjies than surrounding soils and growth stadia would be advanced due to lower water contents (Reasons for this being so will be discussed in more detail in the physiology chapter).

The lower water contents discerned on the heuweltjies in the Robertson study area can partly be attributed to the high concentration of coarse textured lime concretions present in these soils. When lime is present as a fine powder, an opposite effect can be provoked and an increase soil water holding capacity will be the outcome. The role of termites in the accumulation of nutrients is essential in the heuweltjie soils. Termites assimilate a variety of food in the form of plant material into their nest, and as decomposition ensues over time, among other bases, calcium is released and accumulat*es* in the heuweltjie soil which reacts with bicarbonate ions during dry conditions to form calcium carbonate or limestone. Therefore due to the fact that the heuweltjies contain much more coarse textured free lime when compared to non-heuweltjie soils, a lower percentage of the total soil matrix is made up of clay, which ultimately has the effect of a lower soil water holding capacity. In other words, the heuweltjie soil becomes "diluted" with regards to clay content as free lime builds up in the soil at the expense of clay. This occurs only in arid condition where rainfall is insufficient to leach out basic cations from the soil (F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication; Ellis, 2001).

Thus to summarize, much lower general soil water content values are measured in the Robertson study area compared to Stellenbosch due to the drier climate and lower annual rainfall. A substantial difference were observed in the soil water contents of the heuweltjie soils in both the Stellenbosch and Robertson study areas, with Stellenbosch and Robertson displaying opposite trends. The Stellenbosch study area, with a temperate Mediterranean climate, displayed significant higher soil water content on the heuweltjies when compared to non-heuweltjie areas ($P < 0.05$). In the Robertson study area, situated in a semi-arid climate area, results displayed an opposite trend, with the heuweltjies exhibiting significantly lower soil water content when compared to non-heuweltjie areas ($P < 0.05$).

When assessing the origin and reasons behind the differences in soil water contents, variations in soil texture immediately springs to mind as the contributory factor. As already explained, manipulation of the texture of heuweltjie soils by termites is fundamental in establishing the final water content of the heuweltjie soils. Through mixing of sand fractions and incorporation of clay particles and feaces, total porosity is increased thus leading to a higher water storage capacity.

The soil water content is a critical factor, especially in arid and semi-arid regions due to decreasing natural water resources, and needs to be closely monitored to prevent depletion. Agricultural, environmental as well as social interests in our limited water resources can aggravate such circumstances in years where rainfall is inadequate to fulfil the crop water requirement. With the impact of climate change and the concern of water conservation, it is therefore vital to be familiar with the soil and plant water status when grapevines are cultivated, to schedule irrigation in such a manner that water will be utilized as efficiently as possible.

The water content of a specific soil is controlled by the capacity of that soil to store water, which in turns rely on the texture and structure. It also relies on the mechanisms that drive water flux in the soil-water-plant-atmosphere continuum like precipitation, evaporation, surface runoff, interception, transpiration and drainage underneath the rootzone (Konaté, 1999). Thus factors associated with heuweltjies, such as changes in soil structure, higher clay and organic matter contents, and changes in infiltrability and microtopography, may indeed have an effect on surface runoff and interception of rain and irrigation water.

4.2 Chemical properties

4.2.1 pH

In Stellenbosch, different results were obtained on each side of the heuweltjie due to the steep slope. We speculate that nutrients and the basic cations move down slope with gravity and prevailing water movement to accumulate on the edge of the heuweltjie at the bottom side of the slope. Thus, given the specific landscape of the Stellenbosch site as an additional factor, it is clear why the pH values are higher in soils of the north side of the block (bottom of slope) in comparison with the south side (top of slope). No such conclusions could be made for the Robertson due to the absence of a slope.

When the pH values are studied in relation to depth of the soil profile, a clear pattern is observed. The pH of the topsoil decreases with depth in both the heuweltjie and non-heuweltjie plots in Stellenbosch, which indicate probable lime amendments added to the topsoil. This also shows a decline in nutrient levels down the profile. Shange *et al.*, (2006) found similar results in their study of heuweltjies in Stellenbosch vineyards. The pH they found was more or less 0.8 units lower on the non-heuweltjie plots in comparison to the heuweltjie plots. The difference in the pH values in water and KCl indicates the pH dependant charge, which is almost twice as high in the Stellenbosch study area than Robertson.

The pH of the soils in the Robertson study area show far greater values when compared to the Stellenbosch area. This can be ascribed to the lower rainfall that enables the basic cations to accumulate and not leach out. In

Stellenbosch, the cations are leached out and are replaced by cations held in the colloidal soil reservoir such as iron and aluminium. This results in a very low base status and pH.

The pH values on the heuweltjie in the Robertson study area exhibit the exact opposite trends as the values in Stellenbosch when depth is the variable. The pH increases with depth in both the Crest and Edge plots, but decline in the Off plots. This is due to the termite activity in the subsoil of the heuweltjies which accumulates bases and nutrients in the mound.

The reason for the very low pH that was found on the H4O plots, is the high concentration of pirite that is present in the soils of the Robertson area (J.J.N. Lambrechts, Senior researcher Soil Science, U.S., 2010, personal communication). This can give rise to the so called "acid sulphate soils". When undisturbed in the waterlogged condition, they pose little problem and are benign. Draining and excavation of these soils lead to oxidation of the pirite and therefore the formation of sulphuric acid, which brings a significant decrease in pH. Where the pH values fall to below 5.5, availability of phosphates may become inhibited due to precipitation with Al. In these conditions, other ions such as Al, Mn, Zn, Fe, Cu and Co will become more available and thus be taken up more readily, even to toxic amounts. A low pH can also lead to inaccessibility of Ca and Mg which leads to a decrease in growth of vine shoots and roots. Phosphorous is available and mobile only in soils with a pH (KCl) of 6-7.5. It forms compounds with Al and Fe in acid soils and with Ca in calcareous soils, thereby becoming chemically immobile and unavailable for uptake by the grapevine. The low pH values obtained in some of the soils in the Robertson study area can also be ascribed to Na present in the soil in the form of sulphates, and to a lesser degree chlorides. These soils generally contained more soluble salts than the lime-rich soils (Saayman, 1973). The sensible use of gypsum and even agricultural lime can enhance the physical and chemical properties of the soil, thereby establishing an improvement in the growth medium for grapevines. Alkaline and calcareous soils on the other hand cause P to form compounds with Ca, thus becoming insoluble and unavailable for plant uptake. Micronutrients such as mentioned above, become unavailable for uptake by vines causing underdeveloped growth of the vine as well as chlorosis of the leaves. Severe lime-induced chlorosis is noted in soils displaying pH values higher than 8.3. This is due to an iron deficiency and is associated with either a very slow Fe^{2+} uptake, or low concentrations of thereof (Gelat, 1996).

In conclusion, the pH tends to be higher on the heuweltjie than the surrounding soils in both Stellenbosch and Robertson. This is due to the foraging habits of the termites whereby bases emanating from leaves, small twigs and other forms of detritus that termites feed on, accumulate in the termite nest. This could be a problem in Robertson as the pH of the majority of the soils is already quite alkaline. Amendments in the form of ammonium sulphate, ammonium nitrate or sulphur coated urea can be applied on soils where the pH is above 8. As urea is already applied in the soils of the Robertson study area, the problem of an alkaline pH can be overcome by increasing the quantities at each application. Where the pH is low, like in the case of the Stellenbosch and RH4O values, lime amendments are recommended. Where pH values are low due to the presence of pirite, the draining or excavation of soils should be avoided and management practices should be modified accordingly.

4.2.2 Electrical Conductivity

According to Hazelton and Murphy (2007), soils are conventionally classified as saline if they exhibit an ECe value > 4.5 dS/m.

In Stellenbosch, the EC_e values are more or less non-committal because of the high rainfall that leaches away most of the salts. The comparison between the values of the heuweltjie and non-heuweltjie sampling plots are based on differences in EC_e values that are too small. Even though a small difference occurs between the EC_e values taken on the heuweltjie and non-heuweltjie plots, it is not sufficient enough to substantiate any reason for differences in EC_e between the two. Through interpretation of these results it is evident that the EC_e values obtained from the Stellenbosch study site is too low to have any major inhibitory effects on the physiology, growth and normal functioning of the grapevine.

The soils of the Robertson study area contain significantly more soluble salts than Stellenbosch, as deduced from the high EC_e values obtained with saturated paste extracts. This can either be due the specific type of irrigation (drip), the amount of water applied per irrigation interval or the region's natural soil soluble salt content. Due to the study site being situated on a terrace of the Breede River, the soil has a natural high salinity.

When the EC_e values of the heuweltjie soils are studied and compared with the surrounding soils, a clear trend emerges. The values of all the samples of the non-heuweltjie plots average significantly higher than the samples taken at the same depths at both the Crest and Edge plots. Variations are substantial, especially in the subsoil where EC_e values of the non-heuweltjie plots outdo the values of the heuweltjie plots more than two times. This could indicate possible distribution of salts by the termites through their burrowing activity, which can explain the homogeneous distribution of salts in the Crest profile. Before the heuweltjies were exposed to cultivation and soil tillage, easily soluble salts such as sodium could have moved down the slopes of the heuweltjie towards the surrounding soil. This assumption can be substantiated by the exchangeable cation results, which clearly shows a higher Na concentration in the surrounding soils than the heuweltjie soil.

The high EC_e values in the topsoil (0-20cm) can be ascribed to the capillary movement of salts to the soil surface underneath the drippers due to the application of deficit irrigation applied. H2 overall has higher EC_e values than H1 because of the presence of a soft carbonate B horizon in the profile. This indicates the accumulation of free lime, which is an excellent conductor of electricity. The reason for the high EC_e value on H2O is the presence of a dorbank, indicating a high concentration of Na. Na is needed to bring silica into movement for the formation of a dorbank (F. Ellis, Senior lecturer Soil Science, U.S., 2010, personal communication).

The high EC_e values could have a major effect on the vigour and eventual yield of the grapevine. Maas (1990) studied the effects of saline conditions on grapevines. He found a decrease in yield of 9.6% for any unit increase above a threshold value of 150 mS/m. Shani and Ben-Gal (2005) similarly reported that salinity reduced transpiration, biomass production and ultimately vine death.

4.2.3 Exchangeable cations

The extractable cation content in the Robertson soils is far greater than the content of extractable cations in Stellenbosch. This is primarily due to differences in climate, especially rainfall, as the high amount of rainfall in the Stellenbosch study area is responsible for the leaching of the cations. In the Robertson study area, the low rainfall cations accumulate due to low rainfall conditions.

The higher Ca and Mg values of the heuweltjie plots in comparison with the non-heuweltjie plots, in both study areas, can be attributed to termite activity which leads to the accumulation leaves, twigs and other plant litter in the nest, thus transforming the soil that they inhabit into a nutrient sink. Due to the higher turnover of nutrients in the soil, a higher basic cation content is expected. Differences in Na and K contents between the different plots were mostly low and insignificant. However, due to the occurrence of a dorbank, some of the subsoil Na values were very high, as Na plays an essential part in the formation of a dorbank.

Shange *et al.* (2006), who also conducted studies on heuweltjies in the Stellenbosch area, discovered similar findings with higher Ca values on heuweltjie than on non-heuweltjie plots. However, higher K values were detected on the non-heuweltjie-plots than on the heuweltjie plots, which is in contrast with their findings.

In experiments done by Sheikh and Kayani (1982), it was found that only four of the thirteen termite species that were studied (*Odontotermes lokanadi*, *Odontotermes obesus*, *Coptotermes heimi* and *Microtermes unicolor*) were associated with significant higher values of exchangeable calcium in their mounds. In other findings, results showed that termites notably contribute to the incorporation of cation-rich subsoils, together with organic-rich faeces and saliva into their mounds (Black and Okwakol, 1997; Noirot and Darlington, 2000; Holt and Lepage, 2000). When these structures eventually erode, the surface soil becomes enriched in Ca, Mg, Na and K as well as with organic N, P and interstratified clay minerals (Bignell and Holt, 2002).

It could therefore be concluded that a higher exchangeable Ca and Mg content occur in the heuweltjies, both in the Stellenbosch and Robertson study areas. Although insignificant, exchangeable K displayed higher values on the heuweltjie in Robertson, with significantly lower Na values in the subsoil. Thus, the higher nutrient status of the heuweltjie soils will greatly increase its fertility and also its capacity to provide the vines with sufficient nutrients for satisfactory growth and ensuring better wine quality. Due to the fact that water is the critical factor for vegetative growth, especially in arid environments, the vines will not benefit from the higher nutrient status in Robertson. In Stellenbosch however, the increased nutrient status of the heuweltjies, enhanced with its higher soil water content, will lead to excessive vegetative growth which ultimately could prove to be detrimental for wine quality.

4.2.4 Extractable Phosphorus

The P values observed at Stellenbosch were very low in general and any difference between heuweltjie and non-heuweltjie plots proved insignificant when the total P concentration of the soil was taken into account. P is immobile and decreases with depth.

According to López-Hernández *et al.* (2006), the influence termites have on P cycling can be categorized into two groups that are associated with the effect of their feeding and construction on P sorption and P availability:

1. Species that cause an increase in P availability coupled with a decrease in P sorption within termite nests, when compared to surrounding soils eg. the grass foragers (*T. geminates* and *N.ephratae*) and the humus feeders, *C. severus*.
2. Species that cause a decrease in P availability coupled with an increase in P sorption within termite nests, when compared to surrounding soils, eg. the fungus growing termites like *Macrotermes* species.

P availability can be modified by termites through incorporation of plant detritus and soil organic matter into their mounds. However, the amounts vary according to their feeding habits and clear distinctions can be made between herbivorous and humuvirous termites. The overall hypothesis though, was that total P is enriched in termite mounds when compared to surrounding soils (Ruckamp *et al.*, 2010).

In general, mounds show an increase in the total available phosphorous values compared to the surrounding soils. This is clearly demonstrated by Spain *et al.*, (1983), where they found that the mounds of *Amitermes laurensis* contained 32 ppm of phosphorous in comparison to the meager 0.9 ppm for the adjacent soil. According to López-Hernández *et al.* (2006), termite mounds will accumulate up to 2.25 times more P than in surrounding soils. He found that the available as well as the mineralizable organic P was significantly higher in the mounds than adjacent soils. Hedley *et al.*, (1982) found that inorganic P was much higher in mounds than adjacent soil, while the difference in organic P was much less.

Results obtained by Shange *et al.*, (2006) in Stellenbosch were very similar to our findings in the Stellenbosch study area, where they also found lower P values on the heuweltjie in comparison to surrounding soils. No pattern in P distribution can be derived for the Robertson study area and P content seem to be independent of whether or not termites were present in the soil. Thus, the P distribution is most probably attributed to the specific characteristics of the soil and the variation in P could not be credited to termite activity. Results were inconclusive in both study areas, and no meaningful difference in P value could be found in the soils on the heuweltjies in comparison with the adjacent surrounding soils. The role of soil tillage and ploughing could have had a significant effect on this parameter, which through mixing of the heuweltjie and non-heuweltjie soil, may have altered the distribution of P.

4.2.5 Total carbon and nitrogen

“Organic matter can vary greatly, depending on its origin, transformation mode, age, and existing environment, thus its bio-physico-chemical functions and properties vary with different environments." (Senesi *et al.*, 2006)**.** SOM (soil organic material) is high in mineral nutrients, carbon and nitrogen, and the specific amounts vary with age of the SOM as well as with stage of decomposition. Older and more strongly decomposed SOM contains less nitrogen than freshly decomposed SOM and has a less significant effect on vegetative growth. SOM also emits carbon dioxide through microbial respiration in the soil, and will add to the new growth above ground, as well as to the yield (Gladstones, 1992).

Results obtained in the Stellenbosch study area agreed well with the findings of Shange *et al.* (2006), who also found significant higher values of the total C percentage on the heuweltjie than on adjacent soils. This is due to the foraging habits of the harvester termite, which feeds on leaves, twigs and general plant litter. Termites excrete these material and their faeces, as well as decomposed plant litter, has a combined effect of increasing the total C and N percentage. The darker colour of the soils observed on the heuweltjie is also evidence of a higher percentage organic material and supports these results.

Termites have the ability to increase the nutrient status and fertility of the soil by creating their own, termite-made fertilizer and reworking it into the soil *via* burrowing and tunneling. Therefore grapevines growing on these termite infested soils, in this case the heuweltjies, have an advantage over vines growing on the soils that surrounds it, and less stress symptoms in terms of nutrient deficiencies and water stress (as discussed earlier) will be exhibited. Accumulation of organic material greatly improves structure and water retention in soils. This is emphasized by reviewing the results of the neutron probe readings on and off the heuweltjie soils.

The explanation for the high total C percentages found in the soils of the Robertson study area, is due to the presence of $CaCO_3$. A big fraction of the total C percentage measured, forms part of the inorganic form of C. The distribution of C and N percentages in Robertson are much more homogeneous than that of the Stellenbosch results. The lack of significant variation between the different plots indicates that effects of the termites are not as apparent as once thought. This is due to the fact that the termites were driven away by ploughing and soils tillage years ago when the vineyard block was prepared for grapevine planting. The vineyard in the study area in Stellenbosch was established in 2003 on virgin soil, while in Robertson the vineyards were planted in 1997. However, earlier peach and apricot cultivation preceded grapevine cultivation at the Robertson study area. This means earlier soil tillage and cultivation practices could have exterminated the termites much earlier than in the Stellenbosch study area.

The conclusion can be made that the grapevines will grow more vigorous on the heuweltjies in Robertson, but to a lesser extent than in Stellenbosch. The effect of the lower soil water content on the heuweltjie could however eclipse the higher carbon and nitrogen values and restrain the vines to weakened vegetative growth if irrigation is not applied in sufficient amounts.

Termites modify the physical, chemical and biochemical properties of the soil through the process of mound building. Through accumulation and decomposition of leaves, twigs and faecal matter, there is a considerable increase in organic matter content of the mound soils so that C and N are more abundant in the mounds in comparison with surrounding soils. Termites use clay as building material, as well as faecal matter in combination with sandy particles as cement, to construct the inner walls and tunnels of their mound. According to López-Hernández (2001), termite mounds will act as a sinks in the nutrient economy in soils.

Adding to the redistribution of organic matter, termites will also modify the C/N ratio. If the C/N ratio becomes too high, it will inhibit bacterial activity and thus decomposition (Lobry de Bruyn and Conacher, 1990). Studies by Lee and Wood (1971a) show that out of the 30 samples tested, 28 showed an increase in the C/N ratio of the termite mound soil compared to the undisturbed, surrounding soil. Briese (1982) also found accumulation of C, PO_4 and N in the mound soils when compared to adjacent soils. This was due to the decomposition of seeds and plant litter discarded at the entrance of the nest. On the other hand, Wiken *et al.* (1976) suggested that any increase in organic matter content of the disturbed mound soils could perhaps be linked to deposition of somatic exudates, since their binocular examination did not disclose any inclusion of humified matter or forest litter.

4.2.6 Organic carbon

In Stellenbosch, the values of organic carbon percentage are more or less the identical with the total carbon values, indicating the absence of any form of inorganic carbon. The importation of leaves, twig, plant litter and detritus by termites into the mound, will contribute to a higher percentage organic carbon content in the heuweltjie soil, through accumulation and decomposition.

In Robertson, the organic carbon percentages do not correlate with the total carbon percentage values in the same manner that the Stellenbosch values do. This could be due to the occurrence of free lime and the dominance of $CaCO_3$ in the area, especially in the soils that occur on the heuweltjies. The carbon that forms part of the $CaCO_3$ will be included in the measurement of the soil's total carbon content, but not into the organic carbon content as it is an inorganic form of carbon.

The very high organic carbon values in both the 40-60 cm and 80-100 cm samples of the H4E plot, is an indication that the effects of the termite are still evident in some parts of the heuweltjie. Ploughing, tillage and cultivation practices have made it very difficult to estimate where and at what depths significant differences would occur in heuweltjies.

Apart from soil texture, the organic carbon content is an important property influencing the soil's water retention. The textural composition however, will have a major influence on the organic carbon's affect on water retention. The largest increase in soil water retention will occur in sandy and silty soils, while a decrease takes place in finer textured soils (Rawls *et al.*, 2003). They also state that at low carbon contents, an increase in the soil organic carbon content will result in an increase in water retention only in coarse textured soils while the water retention will decrease in finer textured soils. As the initial organic carbon content increases, the sensitivity of water retention to changes in organic matter decreases.

5. CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this chapter were to classify the heuweltjie soils in terms of physical and chemical properties and to establish whether or not any significant differences occur between heuweltjie and non-heuweltjie soils that could affect agricultural activities. These aspects were placed under scrutiny and the resultant implications created much food for thought.

Soil factors play a vital part in variation in growth of grapevines, if taking into consideration the significance of the soil variation that occurs on and off the heuweltjies. In both study areas the soils on the heuweltjies displayed very different characteristics than their adjacent non-heuweltjie neighbours. Distinctions could be made between heuweltjie and non-heuweltjie plots in terms of soil morphological, physical and chemical characteristics.

Very prominent differences were observed in the morphological soil attributes. In Stellenbosch, there was a significant variation in colour as well as structure between the heuweltjie and non-heuweltjie soils, which led to the soil being classified as two different forms, that of Oakleaf and Tukulu respectively. In Robertson, five different soil forms (Augrabies, Brandvlei, Valsrivier, Oakleaf and Oudtshoorn) were distinguished due to the large area of sampling in comparison to Stellenbosch. The main morphological difference between the soils on and off the heuweltjies were the presence of free lime and calcrete remnants (calcrete hardpan broken by ploughing and tillage), associated with the heuweltjie soils.

In Stellenbosch, major differences could be distinguished in terms of soil texture. A higher clay content as well as a higher degree of sand fraction-mixing were observed on the heuweltjies soils. This was due to the termites' ability to incorporate clay into their nest as building material as well as their burrowing activity, respectively. Bulk density values were higher on the heuweltjies than off the heuweltjies, partly due to above mentioned reasons. Differences were not significant though. In Robertson, the same observation was made concerning the mixing of the sand fractions, but clay content showed an opposite trend between heuweltjie and non-heuweltjie soils, with lower clay percentages on the heuweltjies in comparison to the non-heuweltjie soils. This is due to the higher concentration of free lime in the heuweltjie soil, which has the effect of counteracting compaction through its unique composition and chemistry. Due to above mentioned reasons, higher bulk density values were obtained on the non-heuweltjie areas when compared to the heuweltjie soils. Again, the differences were not significant enough to draw a pertinent conclusion.

The results of the soil chemistry analysis paint a clear picture and portray a unique difference between the soils occurring on and off the heuweltjies. Due to the once flourishing termite colony and their activity, the chemistry of the heuweltjie soils differ quite significantly to that of the adjacent surrounding soil.

In the Stellenbosch study area, the pH, total carbon and nitrogen, organic carbon, exchangeable calcium, magnesium and sodium exhibited higher values on the heuweltjie when compared to non-heuweltjie soils. The opposite trend was discerned for exchangeable potassium and extractable phosphorous, which displayed lower values on the heuweltjie soils than non-heuweltjie soils. The results for the total carbon and nitrogen, as well as for organic carbon analysis are significant due to sufficient quantities in the soil to supply a big enough pool for variation. However, the EC, exchangeable cation and extractable phosphorous concentrations of the Stellenbosch soils are quite low due to leaching and any increase obtained did not exhibit sufficient enough variation to defy the very low concentrations originally expected in the soil. Similar results were obtained in the Robertson study area. pH, total carbon and nitrogen, organic carbon, exchangeable calcium, magnesium and potassium, as well as extractable phosphorous displayed higher values on the heuweltjies compared to non-heuweltjie soils. Only the EC and exchangeable sodium exhibited an opposite trend by displaying a lower value on the heuweltjie soils in comparison with non-heuweltjie soils.

The main factor, distinguishing between heuweltjie and non-heuweltjie plots is the soil water content of the soils. It gives rise to considerable variation in vine vigour and after considering all the attributes of heuweltjie-altered soils, it was concluded that this was the single most influential characteristic in terms of differences observed between heuweltjie and non-heuweltjie plots.

Possible mechanisms could be put into place that will successfully estimate the impacts of modified soil attributes on crop (not just grapevines) growth, productivity, and quality, thus giving rise to a new dimension in sustainable agriculture. Models should be developed to predict and indicate the effect of heuweltjie-induced changes on crops, thereby explaining through scientific reasoning the possible changes occurring in eventual crop quality. Since the water relations of heuweltjie versus non-heuweltjie soil are the most distinct point of difference, recommendation is to focus on this aspect and further investigate the reasons behind these variations and anomalies. It could therefore be beneficial to implement different irrigation schedules for vines growing on heuweltjies versus non-heuweltjie areas. This however could prove a very time-consuming, complicated and expensive proposal to carry out.

An aspect not investigated in this study, is the possible variation in micro nutrients between heuweltjie and non-heuweltjie soils. For future studies, it is therefore recommended that a detailed investigation into the micro-nutrient content occurring on and off heuweltjies should be done, coupling it with differences in growth patterns, productivity and wine quality. Still, further research needs to be conducted to investigate certain key aspects as well as questions that arose during this study.

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CHAPTER 4 – ECOPHYSIOLOGY, VIGOUR, BERRY AND WINE QUALITY OF VINES GROWING ON AND OFF HEUWELTJIES

1. INTRODUCTION

The Cape Floral Region (CFR), the smallest of the world's six floristic kingdoms, has recently been assigned as one of the IUCN Global Centers of plant diversity, and is classified by many as being the world's newest hot spot for endemism and plant diversity (Anonymous, 2005). When compared to other Mediterranean-type climatic regions, the CFR contains by far the highest species density and rarity. It occupies only 0.38% of Africa's surface area, but contains 20% of its flora and five out of the twelve endemic families (Duffy, 2008). Of global scientific interest is the plants of this region's exclusive adaption for seed dispersal through myrmecochory (by termites and ants), fire, high levels of plant pollination by insects and its distinctive floristic relicts allowing reconstruction of prehistoric floral populations (Anonymous, 2005).

The CFR comprises the Fynbos Biome and the Succulent Karoo Biome as the two major vegetation types in the Western Cape (Figure 4.1). The Fynbos Biome dominates the CFR, with extraordinary endemism and floral diversity (Rebelo *et al.,* 2006). The Succulent Karoo consists of the highest diversity of succulent plants, and is the world's most species-rich semi-desert (Rutherford *et al.,* 2006). This makes the Western Cape one of the most biodiverse and beautiful places to live in or visit, but also puts a huge responsibility on us as South Africans, to protect this diversity through sustainable conservations practices.

It is almost impossible to describe the majestic backdrop created by the Fynbos when gazing upon Table Mountain, not even to mention the species diversity of its associated vegetation. Fynbos can be translated to English as 'fine bush' and is endemic to a very small area in the Western-Cape (Marot, 2010) and is epitomized by evergreen, fire-prone shrubland. The distinctiveness of the restios (*Restionaceae*), ericoid shrubs (consisting of the families *Rutaceae*, *Rhamnaceae*, *Asteraceae* and *Thymelaeaceae*) plus, of course, the ever popular proteas (*Proteaceae*) characterizes the Fynbos (Rebelo *et al.*, 2006), with the protea even serving as our country's national sport emblem, thereby establishing itself as a vital part of our cultural heritage.

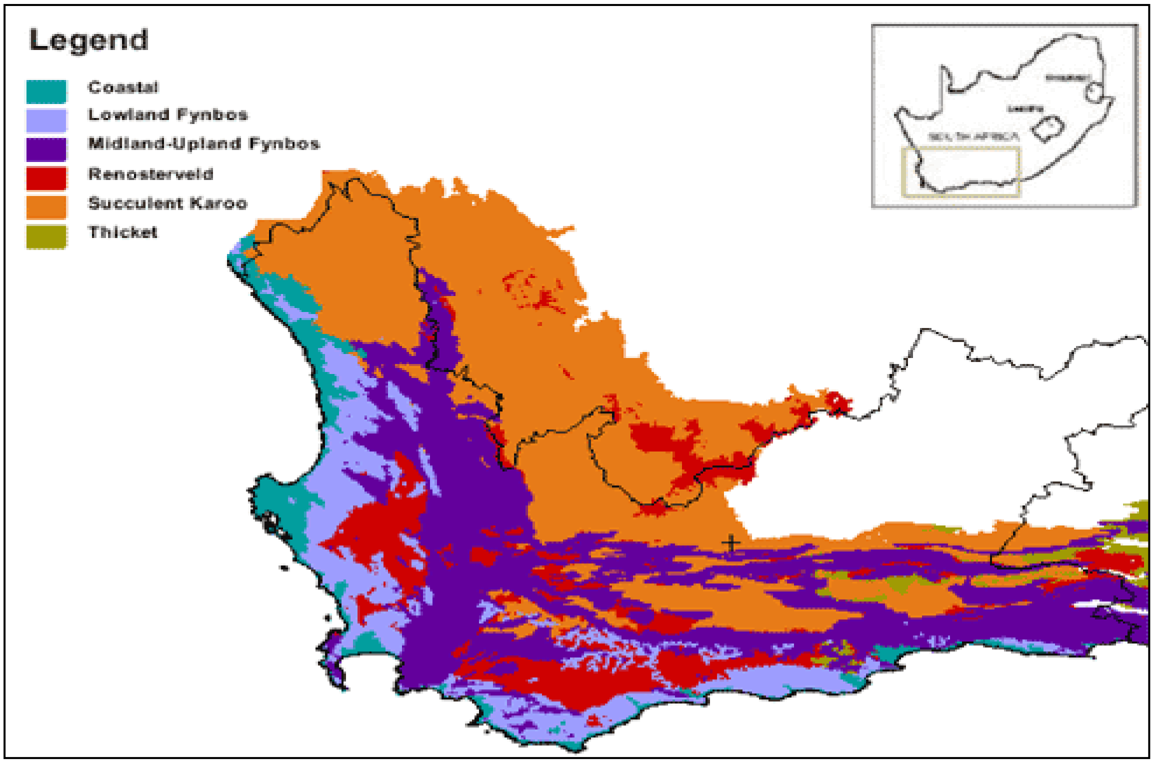

Figure 4.1: Map of the Western Cape indicating the distribution of the different biomes (http://bgis.sanbi.org/wces/biomes.asp - viewed 28 September 2010).

The Succulent Karoo Biome is made up of six bioregions, each being unique and diverse in its own way. The Richtersveld, Namaqualand Hardeveld, Namaqualand Sandveld and Knersvlakte all fall under the Namaqualand region, while the Rainshadow valley and Trans-Escarpment Succulent Karoo, in the rainshadow of the Escarpment and high-altitude semi-desert plains respectively, characterizes the valleys and lowland plains (Mucina *et al.*, 2006). The most prominent feature of this biome is the 1700 species-strong leaf-succulent shrubs (Driver *et al.*, 2003). Families that stand out are the *Aizoaceae* (formerly known as the *Mesembryanthemaceae*) or 'vygies' (Bittrich and Hartmann, 1988), the *Euphorbiaceae* (spurges), Crassulaceae (stone crops), as well as the succulents of *Iridaceae*, *Asteraceae* and *Hyacinthaceae* (Hilton-Taylor, 1996). One of the key factors that inspire variation in the vegetation of arid environments is pedogenic diversification, and mechanisms of water storage, translocation and distribution by the soil, which is fundamental in developing and sustaining ecosystem diversity (Mucina *et al.*, 2006). Agriculture is the focal point of land use outside of the protected reserves, with 90 % of the region subjected to livestock grazing (Driver *et al.*, 2003).

Within the CFR lies the Cape Winelands which provide the Western Cape not only with a major financial boost, but also helps to sustain the economy by offering tourist attractions and creating job opportunities. It is also very much in the objective of the Western Cape wine producers to preserve our indigenous Fynbos, Renosterveld and Succulent Karoo vegetation through sustainable agricultural practices as they are dedicated to prevent further losses of already threatened species (Anoymous, 2009). In addition, these remnants of the original vegetation are also increasingly being recognized as reservoirs of biota that provides major ecosystem services to the agricultural industry, such as pollination.

Viticulture in the Western Cape is practiced from the mountainous coastal regions to the outstretched plains of the Little Karoo, where it is established in the valleys in close proximity to rivers. The Atlantic as well as the Indian Ocean borders the Cape's winegrowing regions, and significantly influences nearby grapes through favourable maritime climate, coastal fog and cool sea breezes. It extends almost 800 km East to West and is subdivided into five main regions – The Breede River Valley, Coastal region, Little Karoo, Olifants River and the Boberg region (Anonymous, 2009). In terms of the agricultural component, the wine industry is the most economically profitable business in the Western Cape (Cape Wine Academy, 2002).

Vineyards located in the Western Cape possess a very unique element that has a significant effect on landscape at micro-level. This element is brought about by the activity of the harvester termite, *Microhodotermes viator*, which builds underground nests leading to the development of the so called 'heuweltjies'. Heuweltjies make up to 60% of the surface area in vineyards that are situated in the Western Cape (Shange *et al.*, 2006) and can modify the landscape considerably due to their high density in some areas.

Spatial variation in vine vigour in vineyards where heuweltjies occur, is quite common. It is apparent that differences in soil physical and chemical properties at a micro scale, underlies the spatial variations (Reynolds *et al.*, 2007). Not considering its cause, spatial variation can lead to subsequent differences in crop maturity, berry and wine characteristics as well as yield (Bramley and Hamilton, 2004), which complicates management of grapevines. It leads to issues concerning the timing and conducting of certain vineyard management practices, and in spite of that, practices like irrigation and fertigation are frequently standardized over entire blocks.

Investigation into diversity and vegetation composition of Succulent Karoo species in the Worcester Veld Reserve, after being rested from grazing for 67 years, display significant differences on heuweltjies when compared to non-heuweltjies sites (Rahlao *et al.,* 2007). They found that heuweltjie sites consistently exhibited greater changes in plant cover and species composition than non-heuweltjie sites. Evergreen shrubs such as *Pteronia incana* and *Rhus indulata* showed considerably higher cover on heuweltjie sites, while stem succulents like *Euphorbia mauritanica* displayed lower cover. Heuweltjie sites comprise of more nutrient-rich soil and are also prone to have a higher percentage of trees, stem succulents and deciduous shrubs in comparison to the non-heuweltjie sites (Midgley and Musil, 1990).

According to Lambers *et al.* (1998), plants that grow more vigorously because of access to more water, generally use water more extravagantly and tend to be less water use efficient. This fast growth leads to higher water stress as carbon fixation come at the expense of water loss due to the fact that the stomata has to stay open to take up carbon. Plants that follow the C3 photosynthesis pathway, e.g. *Vitis vinifera* are especially subject to this. In studies by Lovisolo and Schubert (1998), it was found that grapevines grown in wetter conditions tend to have a higher stomatal conductance than those under irrigated condition. These plants also exhibited a higher level of water stress, as was shown by the predawn and midday water potential readings. These results suggest that while the grapevines on heuweltjies might grow faster due to the potential easier access to water and nutrients, they may also be more water-stressed during the driest part of the season.

According to the SAWIS Statistics of Winegrape Vines Report of 2008, only the Worcester and Robertson wine districts experienced an annual net growth in terms of total wine grape vineyard hectares. There was a decline in all other wine districts' total wine grape vineyard hectares for at least three of the past five years (Figure 4.2). This means there is a steady increase of vineyard uprooting, while plantings are decreasing, perhaps indicating a malaise in this vital industry.

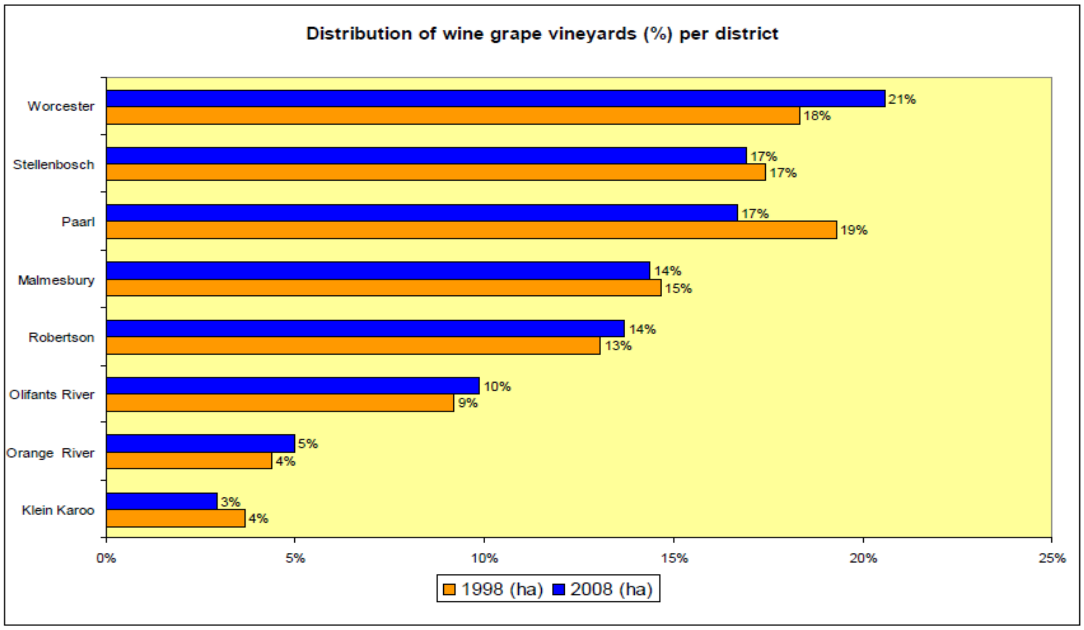

Figure 4.2: Distribution of wine grape vineyards per district in 1998 and 2008 as a percentage of total area (http://www.sawis.co.za).

For the future of the South African wine industry to once again flourish, alternative and creative new ways of managing, and marketing viticulture and wine production needs to be considered. Managing vines growing on heuweltjies in the correct manner could just be the vital injection the South African industry needs to kick dust into the eyes of its competitors.

Heuweltjies cover a large surface area of vineyards in the Western Cape, as already previously stated. If the strategic planning and management of such a vineyard correctly distinguishes between the vines growing on the heuweltjies and the vines growing off the heuweltjies, amazing new possibilities will arise and doors will be opened to give the South African wine industry an edge in terms of variety and diversity. The success of cultivating grapevines on and off heuweltjies in the same vineyard thus depends on how effective the environmental and management factors can be integrated and combined to obtain and sustain competitive yields and wine quality.

The overarching aim of this study was to determine what the effects are of the persistence of heuweltjies in cultivated landscapes in Mediterranean and semi-arid climates on soil characteristics, grapevine vigour and wine quality, and what advantages and disadvantages, if any, this will lend have on agricultural activities.

<u>The objectives of this study surrounding the physiology aspect were:</u>

1. To determine physiological traits/properties of grapevines growing on heuweltjies and adjacent non-heuweltjie areas.
2. To determine the vigour of the grapevines growing on heuweltjies and adjacent non-heuweltjie areas.
3. Determination of grape characteristics and the chemical and sensory attributes of wines from the vines on and off the heuweltjies.

Very little information is available regarding differences in plant phenology associated with grapevines on and off heuweltjies. Quantifying the differences between the heuweltjie areas and those surrounding the heuweltjies, especially regarding wine quality, may assist management decision on the fate of the grapes produced on heuweltjie areas. Therefore, the interrelationship between grapevine characteristics and their impact on the overall vineyard environment must be considered.

2. MATERIALS AND METHODS

2.1 Plant physiology

2.1.1 Stomatal conductance

"Stomatal conductance maximum is a numerical measure of the maximum rate of passage of either water vapour or carbon dioxide through the stomata, or small pores of the plant." (Anonymous, 2010). It plays a vital role in the plant-atmosphere water exchange and is used as a key parameter in many ecological models (Chen *et al.*, 1999). For example, depending on atmospheric conditions, vines with access to large amounts of water will tend to keep its stomata open longer than for vines experiencing drought, thus using more water for every carbon molecule assimilated.

Four vines on each heuweltjie and four vines off the heuweltjie (thus amounting to 16 vines on heuweltjie and 16 off the heuweltjie at each study area) were selected for measuring of stomatal conductance of the plant. On each vine, a healthy mature leave situated in the bunch zone was chosen for experimentation. Stomatal conductance was measured in mmol $m^{-2}s^{-1}$ with a Decagon porometer (Model SC-1). The device was placed on the leaves so that readings could take place on the basal side of each leave, thus measuring the activity and conductance of the stomata.

2.1.2 Leaf water potential

Water potential (Ψ_w) is defined as the status of water in the atmosphere, plants and soil, and can therefore be described as the chemical potential of water per unit volume relative to the chemical potential of pure water at reference conditions (Lambers *et al.*, 1998).

Leaf stem water potential was measured with a pressure chamber (Pockman and Sperry, 2000) during the summer months (December to March) when the vines were subjected to water stress. Predawn (04h00 – 05h00) and midday (12h00 – 14h00) readings were taken to obtain the maximum and minimum water potentials to indicate the amount of water stress endured by the vines. Healthy, fresh leaves together with their stems were cut and measurements took place on site. The same methodology was followed as with the stomatal conductance readings (16 leaves on heuweltjie and 16 off the heuweltjie at each study area).

2.1.3 Measurement of trunk circumference

Trunk circumference was measured to indicate differences between the vines growing on and off the heuweltjies. A measuring tape was placed around the trunk of six vines on the heuweltjies and six vines growing on the adjacent soil surrounding the heuweltjies. Measurements of the trunk were taken 10cm above the scion. Measurements were done at all four sites on and off the heuweltjie, both in Stellenbosch and Robertson.

2.1.4 Determination of pruning mass

The pruning dates of the specific blocks were as follows:

- Stellenbosch – 25 August
- Robertson – 19 August

Twelve vines were pruned, both on and off the heuweltije, so that the pruning mass of each vine could be weighed separately. By comparing the vigour of the vines growing on the heuweltjie to the vines growing on adjacent soil, significant differences in vigour could be determined. The vines were pruned according to the traditional short bearer system, used in commercial wine farming. The shoots from each vine were collected, bunched together and weighed using a spring-balance. Trial tests were also carried out on four vines at each site to indicate detailed differences between the vigour and growing patterns of the vines growing on and off the heuweltjies. The following were calculated in the trial tests:

- Length and mass of main shoot
- Length and mass of lateral shoots
- Number of main shoots
- Number of lateral shoots
- Number of nodia on each shoot

The measurement was repeated at all four sites on and off the heuweltjie in both the study areas to acquire conclusive results.

2.2 Berry analysis

Approximately fifty berries were harvested by hand (1 month before actual harvest) at each site in both Stellenbosch and Robertson to measure the sugar content, titratable acidity (TA) and pH. Berries were selected randomly from bunches on and off the heuweltjie. It was made certain that berries were selected from all parts of the bunch, e.g. front, back, top, bottom.

Once the berries were harvested, analysis was done on the same day to prevent any alteration in sugar and acid content. The fifty berries from each site were weighed after which the volume was determined by the use of a 1 dm^3 cylinder filled halfway with water. The amount of displacement of the water when the grapes were poured into the cylinder was taken to be the volume of the grapes in cm^{-3}.

After weighing and determining the volume, the berries were crushed and approximately four or five drops of juice was placed on the refractometer`s prism assembly. After waiting for about ten seconds, the sugar concentration was measured in percentage Brix (relative weight of sugar in a sample compared with distilled water). 50 ml of juice from each site was then pipetted into a glass beaker and used for determination of titratable acid concentration and pH. This was done through titration with NaOH using a Metrohm 785 DMP Titrino.

2.3 Wine

Grape bunches were selected so that a random sample was obtained on and off heuweltjies. The grapes were harvested by hand using pruning scissors where after it was transported to the Department of Viticulture and Oenology of Stellenbosch University, where the wine was made according to a standard method. Four bottles of wine was made from each site in both Stellenbosch and Robertson.

2.3.1 Wine chemical analysis

After the wine was bottled it was chemically analyzed by a Winescan, where after it was sent to the Department of Food Science of Stellenbosch University to have sensory analyses done on it.

2.3.2 Wine sensory analysis

A descriptive analysis was carried out to determine differences in the recognized organoleptic profiles between the wines emanating from heuweltjie and non-heuweltjie plots. The analysis entailed the tasting of the wine, as well as objective categorization of the wine according to taste and aroma by a chosen panel of ten trained tasters.

Internationally, descriptive sensory analysis has been used in the profiling of food products. This profiling technique is used to determine the sensory quality attributes of food and beverages using a trained panel of judges. In this study the panel of ten judges were trained according to the consensus method (Lawless & Heymann, 1998) and tested for consistency. The panel used a 100 mm unstructured line scale to analyze the eight wine samples for the respective sensory attributes (Table 4.1). For the Cabernet Sauvignon, each treatment was replicated three times, whereas the Shiraz was replicated four times.

The wine samples were presented in a complete randomized order. The sample size was 40 mL and the treatments were served at room temperature (21°C) in ISO wine tasting glasses covered with plastic lids to concentrate the aroma in the headspace. Each sample was coded with a three digit random code. The judges used distilled water and unsalted fat free biscuits (Water Biscuits, Woolworths) to refresh their mouth. All analyses were conducted in a light- and temperature-controlled room (21°C).

The following eight Cabernet sauvignon (Stellenbosch) and six Shiraz (Robertson) samples were tested for a spectrum of sensory attributes (Table 4.1):

- **Stellenbosch**: Sample SH1C = On 1, Sample SH1O = Off 1, Sample SH2C = On 2, Sample SH2O = Off 2, Sample SH3C = On 3, Sample SH3O = Off 3, Sample SH4C = On 4, Sample SH4O = Off 4
- **Robertson**: Sample RH1C = On 1, Sample RH1O = Off 1, Sample RH2C = On 2, Sample RH2O = Off 2, Sample RH3C = On 3, Sample RH3O = Off 3

Table 4.1: Descriptors for the respective sensory attributes of the Cabernet Sauvignon and Shiraz treatments.

Sensory attributes		Descriptors
Aroma attributes	Fruity aroma	0 = None; 100 = Prominent fruity aroma
	Berry jam aroma	0 = None; 100 = Prominent berry jam aroma
	Blackberry aroma	0 = None; 100 = Prominent blackberry aroma
	Vegetative aroma	0 = None; 100 = Prominent vegetative aroma
	Savoury aroma	0 = None; 100 = Prominent savoury aroma
	Spicy / Pepper aroma	0 = None; 100 = Prominent spicy/black pepper aroma
	Balsamic vinegar aroma	0 = None; 100 = Prominent balsamic vinegar aroma
Palate attributes	Fruity flavour	0 = None; 100 = Prominent fruity flavour
	Vegetative flavour	0 = None; 100 = Prominent vegetative flavour
	Savoury flavour	0 = None; 100 = Prominent savoury flavour
	Sweet taste	0 = None; 100 = Prominent sweet taste
	Sour taste	0 = None; 100 = Prominent sour taste
	Bitter	0 = None; 100 = Prominent bitter taste
	Astringency	0 = None; 100 = Prominent astringency
	Alcohol burn	0 = None; 100 = Prominent alcohol burn sensation

2.4 Climate

Weather data was gathered from the specific farm managers at both wine farms, which gathers their information from weather stations situated on the farm and nearby locations (See Appendix 4.1 and 4.2). A weather station is located on the Robertson study area. However, since there is no station on the Stellenbosch study area, weather data was obtained from the Alto weather station situated very close by (within 5km).

2.5 Statistical analyses

2.5.1 Physiology, growth data, berry characteristics and wine chemical attributes

In order to avoid pseudoreplication (for stomatal conductance, water potentials and canopy density/light readings), data for each sampled leaf, or individual measurement were combined to arrive at a mean for each heuweltjie and non-heuwltjie plot. These means were then used for statistical analyses. Physiology results obtained were statistically analyzed using factorial ANOVA's followed by Fisher's LSD posthoc test using the package Statistica Release 9 while growth, berry characteristics and wine chemical attributes were analyzed by the use of descriptive statistics and paired t-tests (Microsoft Excel, 2007). For berry and wine chemical analysis, berries from individual vines on the heuweltjie were combined before analysis, and the same procedure was followed for the non-heuweltjie area. Berries for wine chemical and sensory analysis were treated in the same way.

2.5.2 Wine sensory analysis

For the descriptive sensory analysis, a randomized complete block design was used with eight treatments and four replications for the Cabernet Sauvignon, and six treatments and four replications for Shiraz. All data were subjected to test-retest analyses of variance (ANOVA) using SAS® software (Version 9; SAS® Institute Inc, Cary, USA) to test for reliability, i.e. temporal stability (Judge*Replication interaction) and internal consistency (Judge*Level interaction) (SAS®, 2002). The Shapiro-Wilk test was used to test for non-normality (Shapiro & Wilk, 1965). If non-normality was significant ($P \leq 0.05$) and caused by skewness, the outliers were identified and removed until the data were normal or symmetrically distributed (Glass *et al.,* 1972). Using SAS® line plots indicating temporal stability and internal consistency, single odd judges were identified and removed. PanelCheck software (Version 1.3.1, Nofima, Norway) was used to substantiate the latter results, therefore testing for panel reliability. The final analysis of variance (ANOVA) was performed after the above-mentioned procedures have taken place; where after the least significant difference (LSD) was calculated at the 5% significance level to compare treatment means.

Discriminant analysis (DA) and Principal Component Analysis (PCA) were performed on responses for the different judges of the different treatments. Multivariate data analyses were performed using the XLStat software (Version 2009.5.0.1, Addinsoft, SARL, Paris, France). The DA was performed to classify the wines produced from the heuweltjie and non-heuweltjie plots according to sensory attributes. Similarly, the PCA was performed to determine the association between the sensory attributes of the wines produced from the respective heuweltjie and non-heuweltjie plots. These attributes were then correlated with specific chemical characteristics.

3. RESULTS

3.1 Plant physiology

Before any experiments and analyses were done, a couple of very interesting observations were made concerning differences in plant growth as well as differences in time of specific growth stadia on and off the heuweltjies. Figure 4.3 shows the different growth patterns of the cover crop on and off the heuweltjie at Robertson. It is quite apparent that the initial growth of the cover crop is haltered by the properties of the heuweltjie soil.

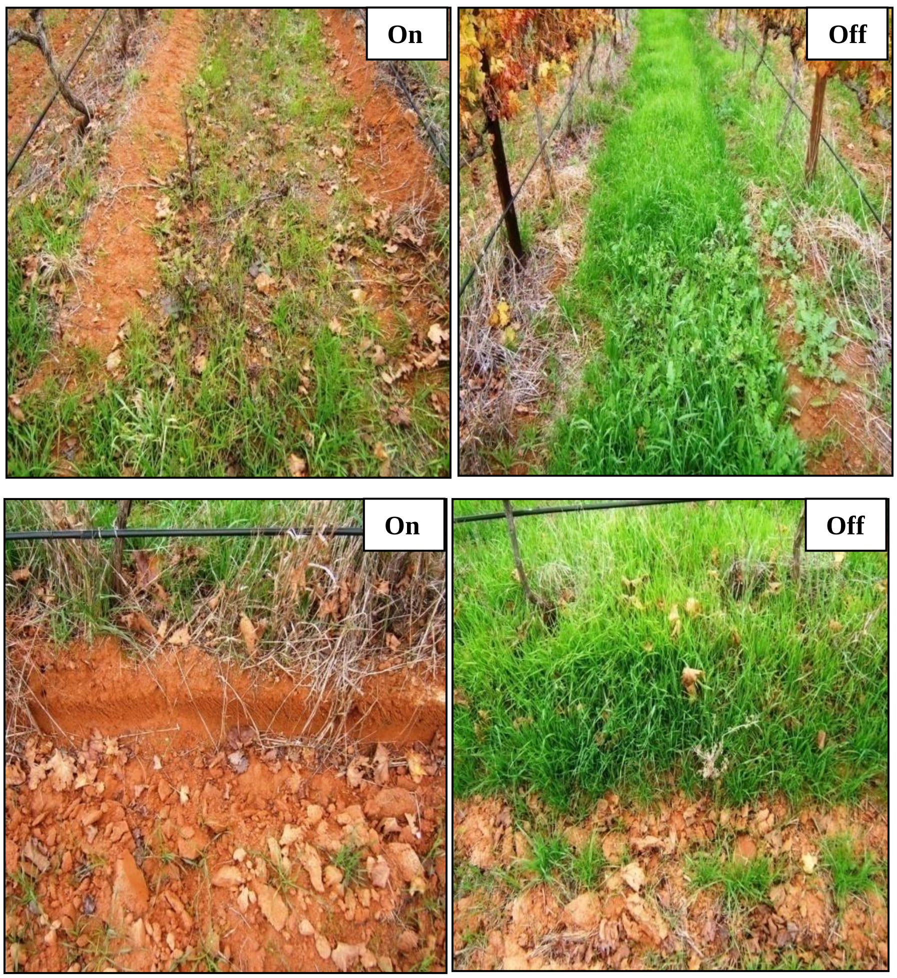

Figure 4.3: Difference in growth of the cover crop on and off the heuweltjie 2 (Robertson - 12 June 2009).

Another observation was the difference in time of leaf shedding of grapevines on and off the heuweltjie (Figure 4.4). Leaf shedding of the vines on the heuweltjies is significantly accelerated in comparison to the vines growing on the adjacent soils.

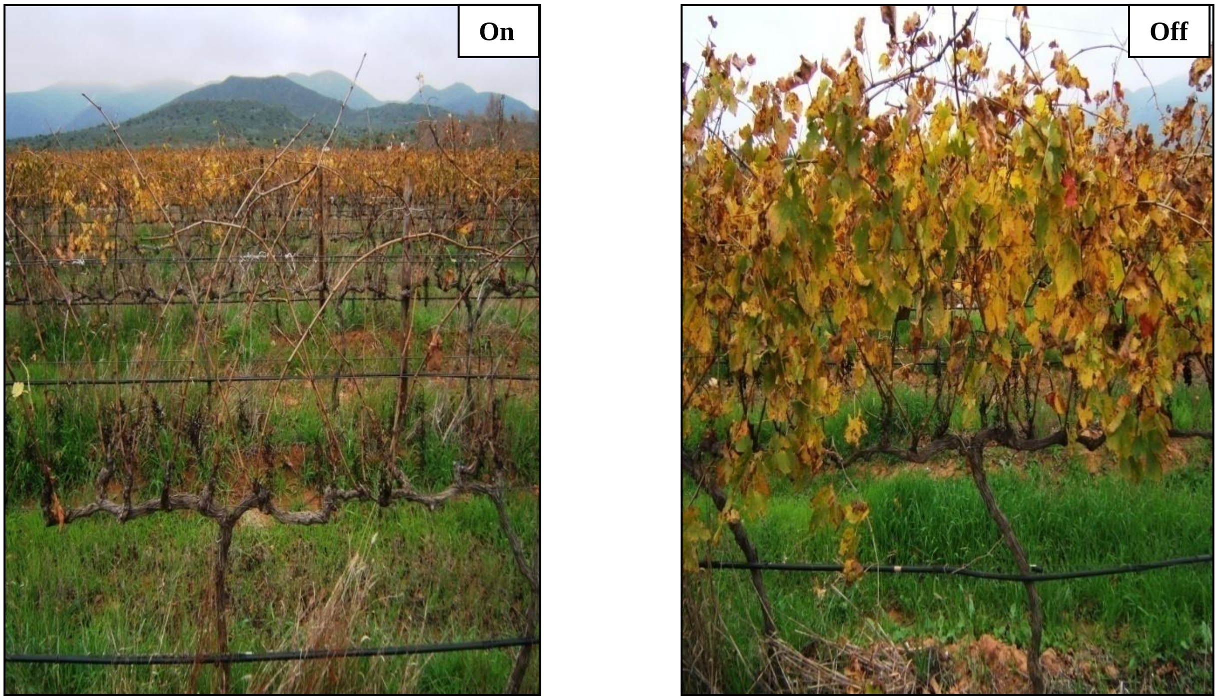

Figure 4.4: Difference in time of leaf shedding on and off heuweltjie 2 respectively (Robertson - 12 June 2009).

Stellenbosch and Robertson are classified in two different climate zones and variations in climatic conditions are substantial. Therefore no discussion of comparisons and dissimilarities are made between results of the physiological traits, vigour, grape characteristics and wine chemical and sensory attributes of the two study areas, only between the specific sites in each study area.

3.1.1 Stomatal conductance

<u>3.1.1.1 Stellenbosch</u>

Readings were taken over a period of five months. Measurements began in December 2009 with the last measurement taking place in April 2010. The reason for measurements in the summer, was the lower soil water content expected due to higher temperatures and lower rainfall. The result is higher water stress and better observation of the variation of water content between heuweltjie and surrounding soils.

Differences between heuweltjie and non-heuweltjie plots were significant in the months of January and March ($p < 0.05$), and in both cases, vines growing on the heuweltjie showed higher stomal conductance. No differences were observed for December, February and April ($p > 0.05$). The values observed in February were very low, due to the amount of cloud cover on the day of measurement. Overall, the actual values for vines growing on the heuweltjie were always higher that for non-heuveltjie vines, which supports the canopy density results.

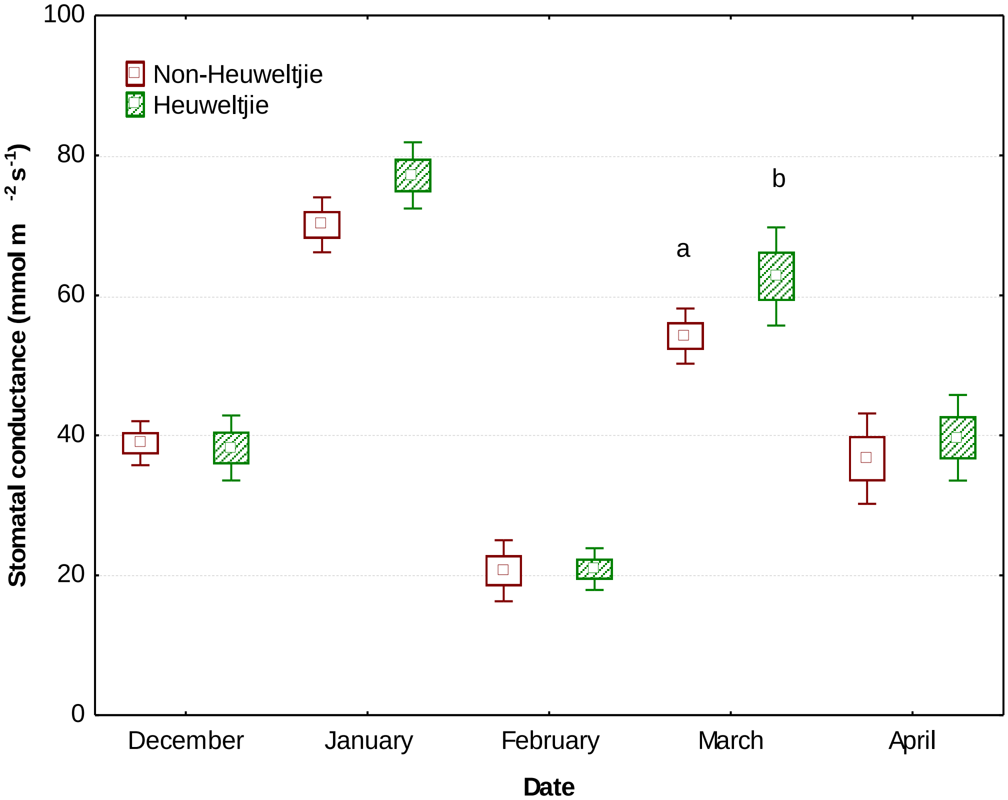

Figure 4.5: Stomatal conductance values of heuweltjie and non-heuweltjie plots in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test ($p < 0.05$; paired t-test).

3.1.1.2 Robertson

Initial plans were to take measurements in the summer, over a period of five months (December - April). However, the weather intervened and a massive hail storm hit Robertson in February, destroying most leaves, shoots and bunches in the study area. Thus, it was no longer possible to measure stomatal conductance on leaves that were damaged in the way it was. The result was that measurements were taken over three months, from December to February.

Stomatal conductance values for Robertson was slightly lower than recorder for Stellenbosch, but no significant differences between heuwltjie and non-heuweltjie areas were found. However, the untimely occurrence of a hail storm hampered further measurements in March and April and results are thus incomplete.

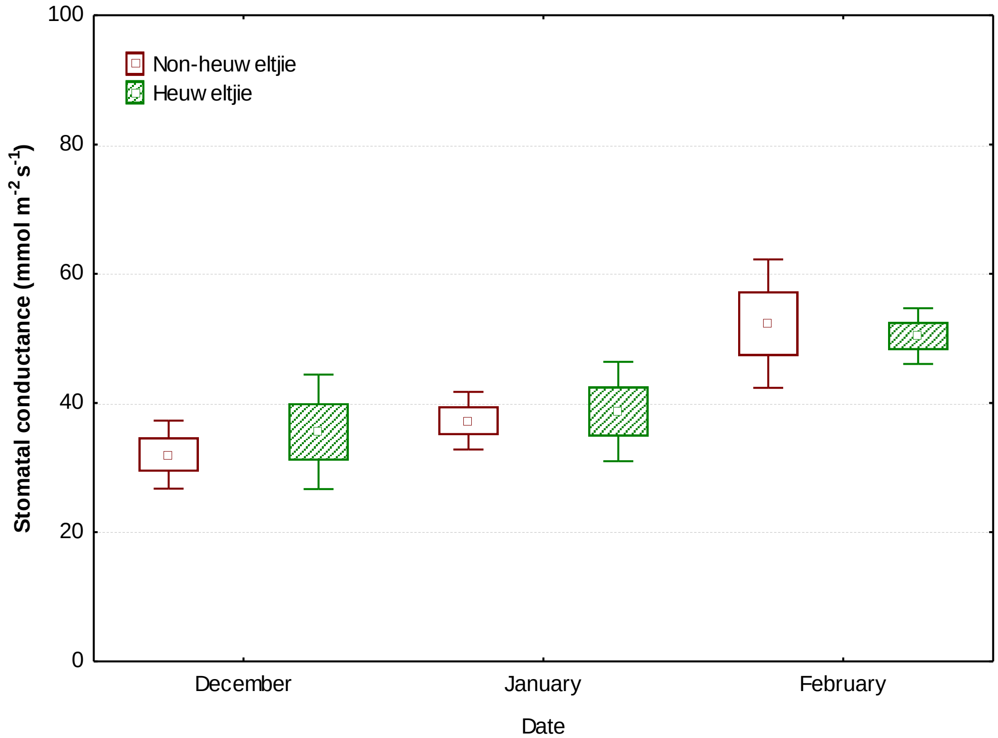

Figure 4.6: Stomatal conductance values of heuweltjie and non-heuweltjie plots in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test.

3.1.2.1. Predawn leaf water potential

3.1.2.1.1 Stellenbosch

There was a steady increase in the temperature as the summer progressed (from 15°C in December to 17°C in March) and then declining to 14°C in April, as autumn commence). Along with this decrease, a decline in the leaf water potential was also observed as clearly indicated in Figure 4.7.

Due to the fact that irrigation is applied in the vineyard block where measurements were made, the predawn water potential (Ψ_{max}) values in general were reasonably high and results were considerably influenced. The lowest (more negative) average predawn value was -4.0 bar, obtained in January on the non-heuweltjie plots, with the highest (less negative) value of -1.59 bar in March on the heuweltjie plots. According to these values, the highest degree of predawn water stress was experienced in January. There were no significant differences between heuweltjies and non-heuweltjie areas.

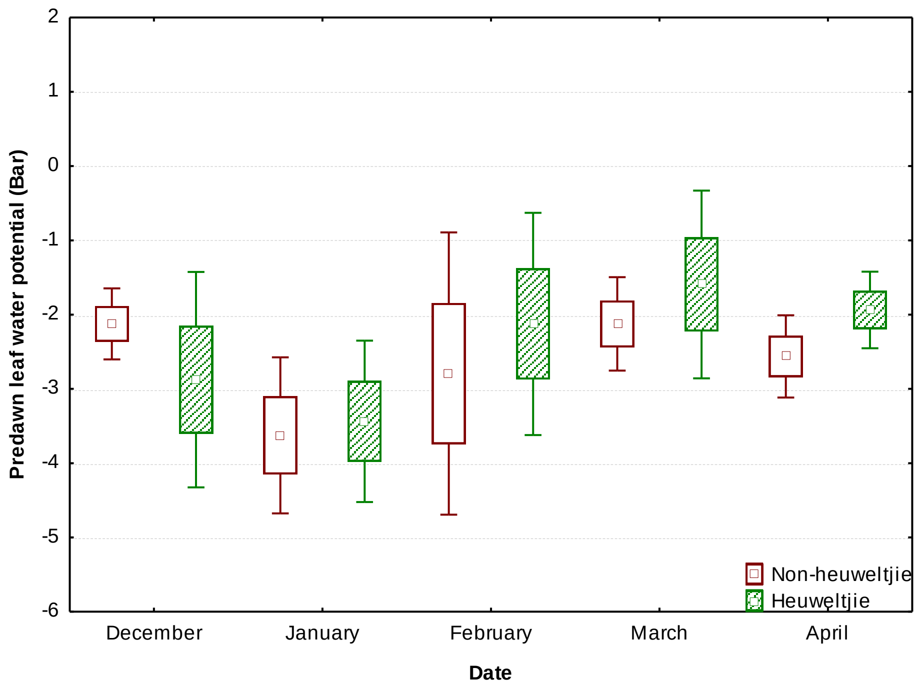

Figure 4.7: Predawn leaf water potential values of heuweltjie and non-heuweltjie plots from December 2009 to April 2010 in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test.

<u>3.1.2.1.2 Robertson</u>

The average predawn temperatures for December, January and February was 14, 16 and 16°C respectively.

The average Ψ_{max} range from -3.91 bar on the heuweltjies in December, to -0.13 bar on the non-heuweltjie plots in January. As the season progressed the values indicate that the vines exhibited higher Ψ_{max} values and thus became less water stressed (Figure 4.8). The grapevines associated with the heuweltjies exhibited lower absolute Ψ_{max} values in comparison non-heuweltjie vines but this was not significant ($p = 0{,}06$), though overall the values were significantly lower in December than other months. In January and February results on and off the heuweltjie were very similar and differences were insignificant ($p > 0.05$).

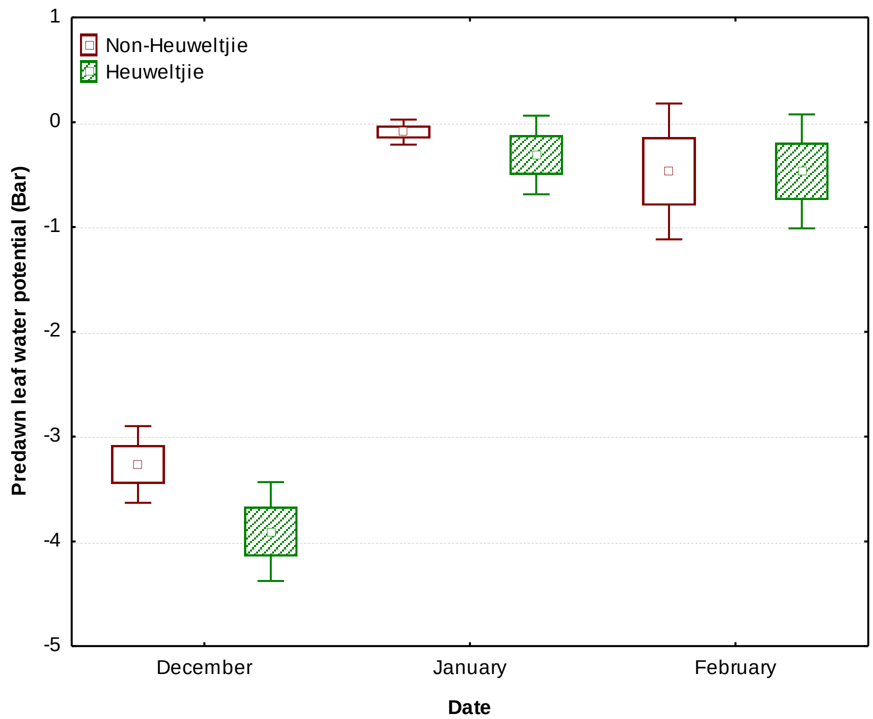

Figure 4.8: Predawn leaf water potential values of heuweltjie and non-heuweltjie plots of the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test.

3.1.2.2 Midday leaf water potential

3.1.2.2.1 Stellenbosch

A similar trend to the Ψ_{max} values is observed with the midday water potential (Ψ_{min}) values, with the heuweltije plots displaying higher absolute values than the non-heuweltjie plots though insignificant ($p > 0.05$). The average Ψ_{min} values range from -15.06 bar, detected in January on the heuweltjie, to -21.25 in March, also on the heuweltjie plots. Average monthly temperature ranged from 29.37°C in February to 24.27°C in April.

Similar to the Ψ_{max} results, there were no significant differences observed between heuweltjies and non-heuweltjie plots wher measuring Ψ_{min}. However, an overall trend of declining Ψ_{min} was observed as the dry season progressed (Figure 4.9).

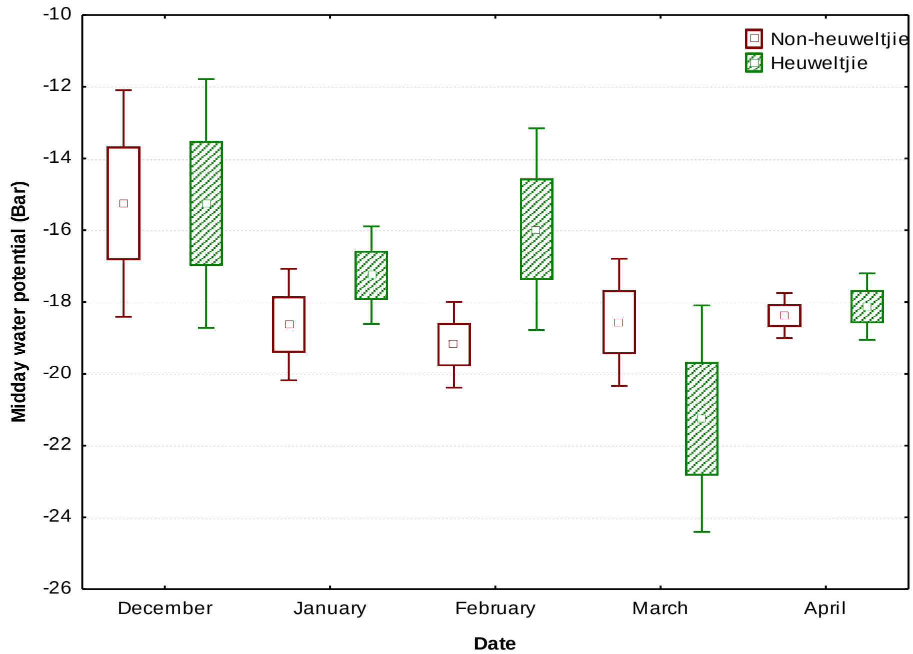

Figure 4.9: Midday leaf water potential values of heuweltjie and non-heuweltjie plots in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test.

<u>3.1.2.2.2 Robertson</u>

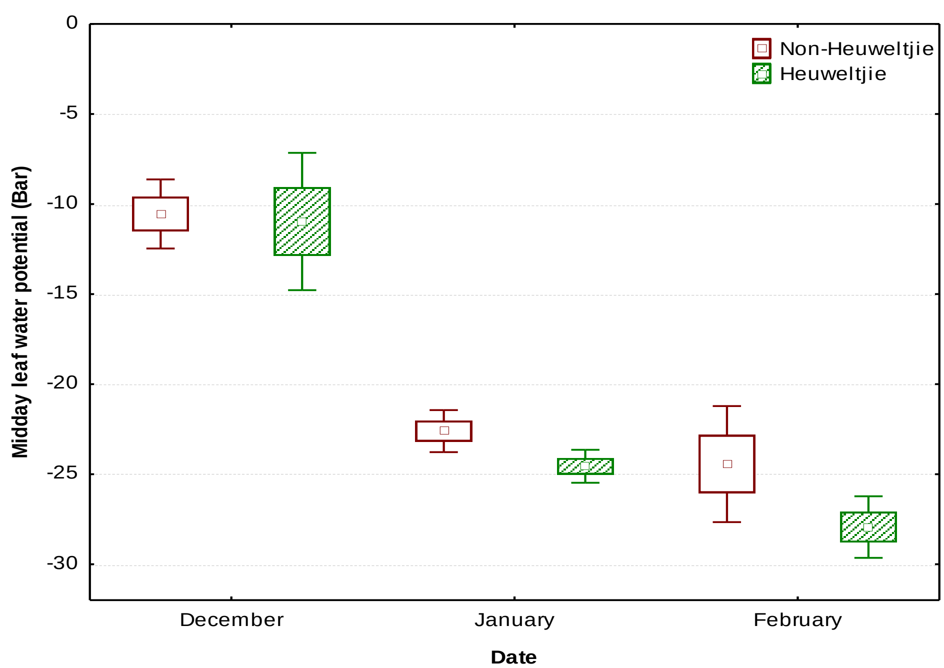

Figure 4.10: Midday leaf water potential values of heuweltjie and non-heuweltjie plots of the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. A factorial ANOVA was used for statistical analysis, followed by the Fisher's LSD posthoc test.

The average midday temperature of December -, January - and February 2009 was 32, 35 and 33°C respectively. This means water is evaporating faster and in higher quantities as the season progresses and can ultimately have an effect on the plant-water relations.

In contrast to the Ψ_{max}, the Ψ_{min} indicates a decrease in the values with the progressing of the season, which signifies increasing water stress. This decrease in Ψ_{min} is proportional to the increase in temperature as the summer advanced as well as with the coupled drying out of the soil (seesChapter 3). The average Ψ_{min} values range from -27.94 bar in February on the heuweltjie to -10.13 bar in December on the non-heuweltjie plots. As shown in Figure 4.10, the grapevines associated with the heuweltjies seem to display lower Ψ_{min} values than the vines growing on the surrounding soils (especially with the progression of the dry season) indicating higher levels of water stress. Differences between heuweltjie and non-heuweltjie plots were insignificant during December and January ($p > 0.05$), while it was nearly significant during February ($p = 0.051$).

3.1.3 Canopy density

<u>3.1.3.1 Stellenbosch</u>

A significant delay in the time of budburst was observed on the heuweltjie-associated vines in the Stellenbosch study area, as illustrated by Figure 4.11.

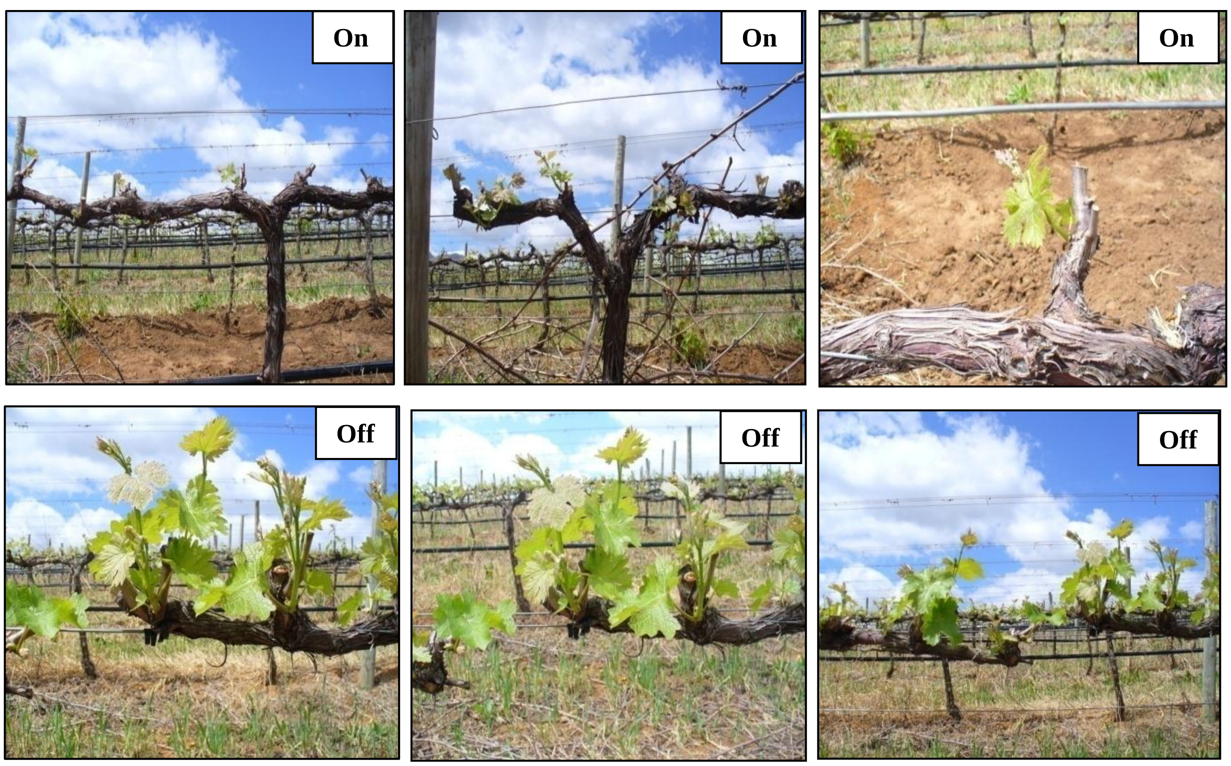

Figure 4.11: Delay of early growth stadia on heuweltjie in comparison with normal growth off the heuweltjie (b) (08/10/2009).

In the later stages during the growing season, exceedingly vigorous growth is observed on the heuweltjie-associated vines when compared to the corresponding non-heuweltjie vines (Figure 4.12).

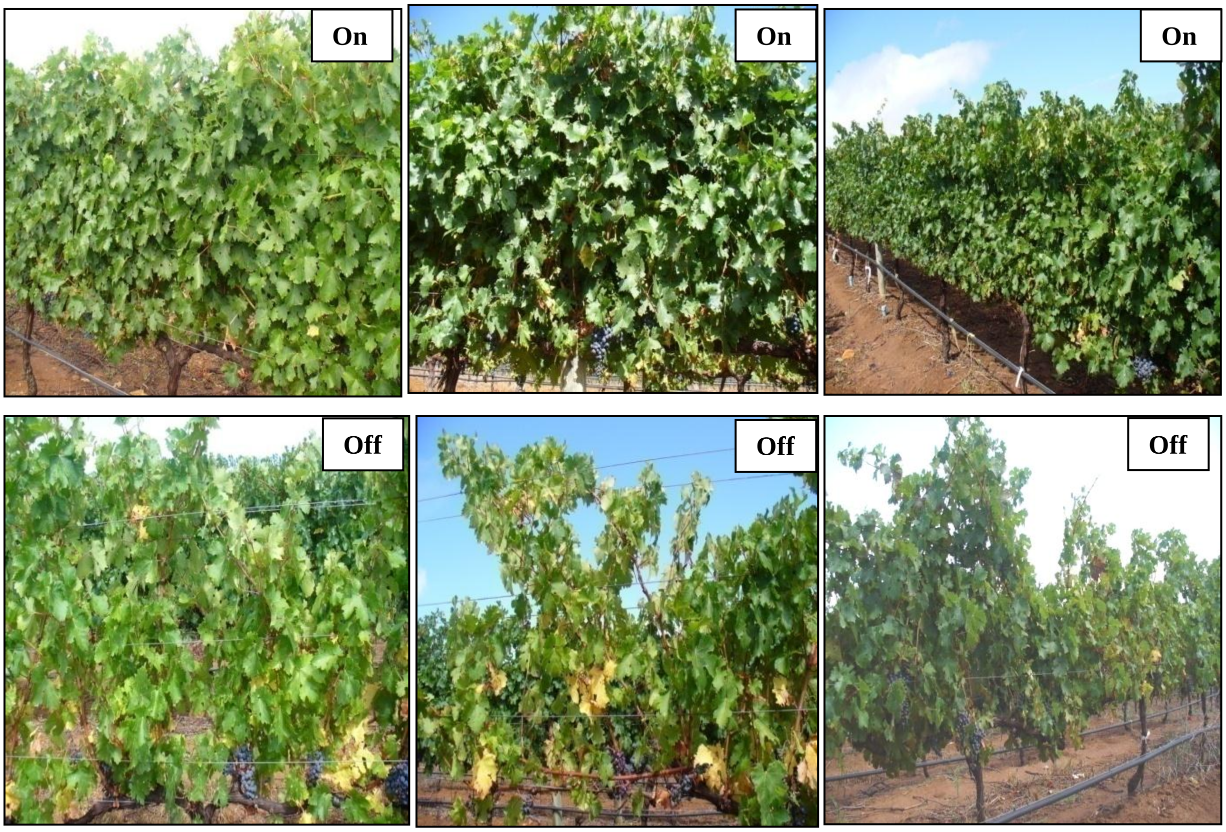

Figure 4.12: Distinction between the vigour of vines growing on and off the heuweltjies in the Stellenbosch study area (25/02/2010).

A very clear pattern is discerned in the canopy light measurements at different stages during the season. According to the ceptometer values (Table 4.2), the vegetative growth on the heuweltjie experienced a lag phase in the early summer. After this initial delay, the vegetative growth of the vines on the heuweltjie increased considerably, surpassing the growth of the non-heuweltjie vines.

Differences in canopy light readings between heuweltjie and non-heuweltjie plots are apparent for all the months. Similar observations were made in December and January, with higher canopy light readings obtained on the heuweltjie plots when compared to non-heuweltjie plots ($p > 0.05$). There were no differences in average light radiation and percentage light radiation reaching the bunch zone in December and January and the first significant differences ($p < 0 .05$) was in February. Lower average light radiation and a higher percentage light radiation reaching the bunch zone were measured; this continued until April.

Table 4.2: Means (±SE) of the light radiation (µ E m^{-2} s^{-1}) in the canopy of grapevines on and off heuweltjies as well as the average percentage of light reaching the bunch zone in months in the Stellenbosch study area. Sites were compared using a paired t-test. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

Average ceptometer value					
Plot	**December**	**January**	**February**	**March**	**April**
Non-heuweltjie	26.75(±4.03)a	35.94(±1.68)a	62.81(±3.18)a	80.31(±1.66)a	92.19(±8.410a
Heuweltjie	31.81(±7.25)a	39.69(±3.19)a	33.94(±3.26)b	30.5(±0.97)b	17.63(±2.52)b
	Average % of total light radiation reaching the bunch zone				
Non-heuweltjie	1.08(±0.16)a	2.00(±0.09)a	3.56(±0.18)a	4.21(±0.09)a	5.03(±0.46)a
Heuweltjie	1.28(±0.29)a	2.20(±0.18)a	1.92(±0.18)b	1.60(±0.05)b	0.96(±0.14)b

3.1.3.2 Robertson

By examining photographs taken of the canopy (Figure 4.13) and through speculative evaluation, it could be concluded that the canopy density of the vines is much higher on the non-heuweltjie plots in comparison to the vines associated with the heuweltjie. This also correlates very well with the soil water measurements, which indicates much higher average soil water contents on the non-heuweltjie plots when compared to the heuweltjie plots.

Variations were observed in the readings obtained from the heuweltjie and non-heuweltjie plots (Table 4.3). Heuweltjie plots exhibited higher absolute canopy light readings in all three of the months, with January and February displaying significant differences (p < 0.05). It seemed that as the growing season lapsed, a greater difference emerged between heuweltjie and non-heuweltjie plots.

Table 4.3: Means (±SE) of the light radiation (µ E m^{-2} s^{-1}) in the canopy of grapevines on and off heuweltjies as well as the average percentage of light reaching the bunch zone in different stadia of the season in the Robertson study area. Sites were compared using a paired t-test. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

Average ceptometer value			
Plot	**December**	**January**	**February**
Non-heuweltjie	26.69(±3.45)a	29.65(±1.65)a	28.47(±1.01)a
Heuweltjie	38.56(±5.33)a	57.69(±3.13)b	67.44(±2.21)b
	Average % of total light radiation reaching the bunch zone		
Non-heuweltjie	1.35(±0.17)a	1.76(±0.10)a	1.54(±0.05)a
Heuweltjie	1.95(±0.27)a	3.43(±0.19)b	3.65(±0.17)b

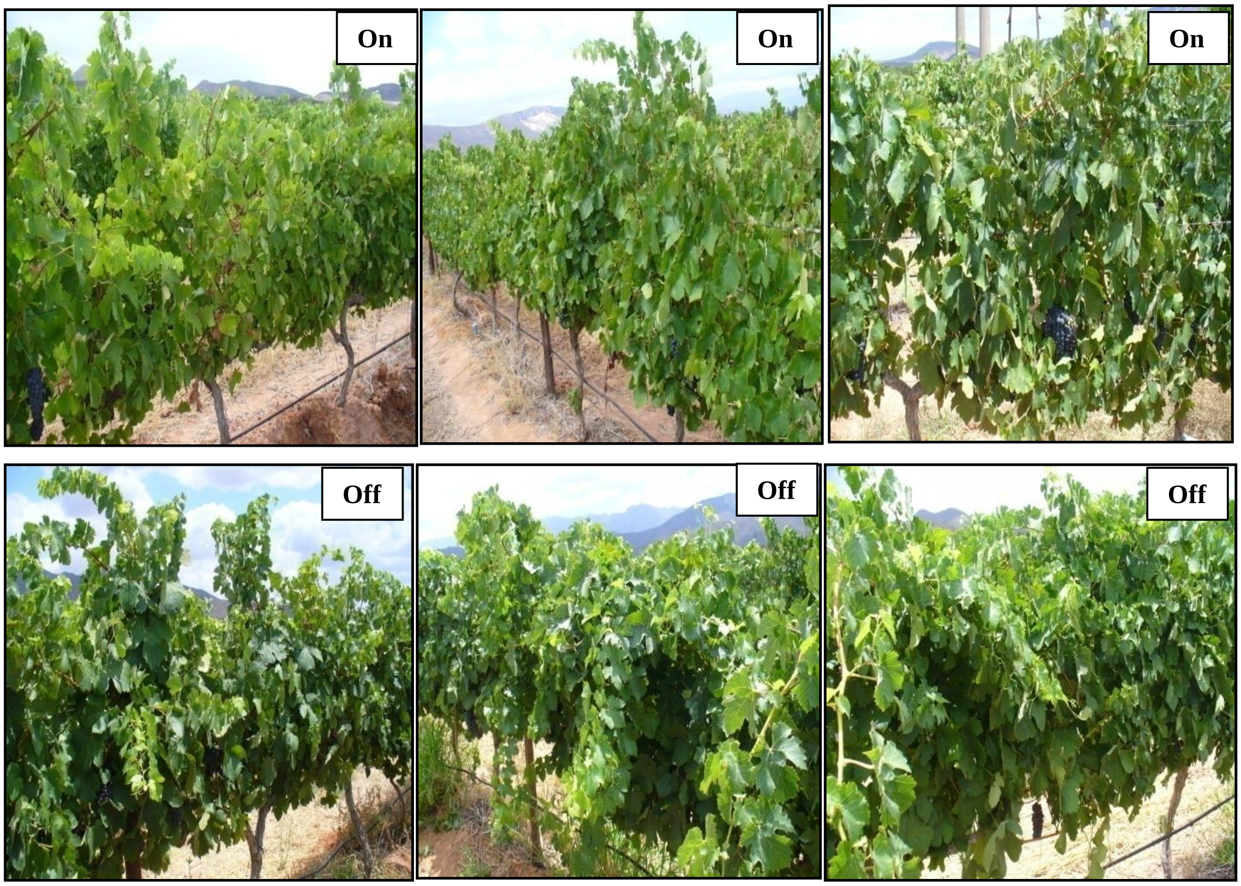

Figure 4.13: Distinction between the vigour of vines growing a) on and b) off the heuweltjies in the Robertson study area (27/01/2010).

3.1.4 Trunk circumference

<u>3.1.4.1 Stellenbosch</u>

The results obtained from grapevine's trunk circumference measurements were quite substantial. Vines associated with the heuweltjies showed significantly larger trunk circumference values than the non-heuweltjie vines ($p < 0.05$). The average value on the heuweltjie was 17.1 cm in comparison to 15.6 cm on the non-heuweltjie vines. Values ranged from 14.0 cm on H4O to 21.0 cm on H4C.

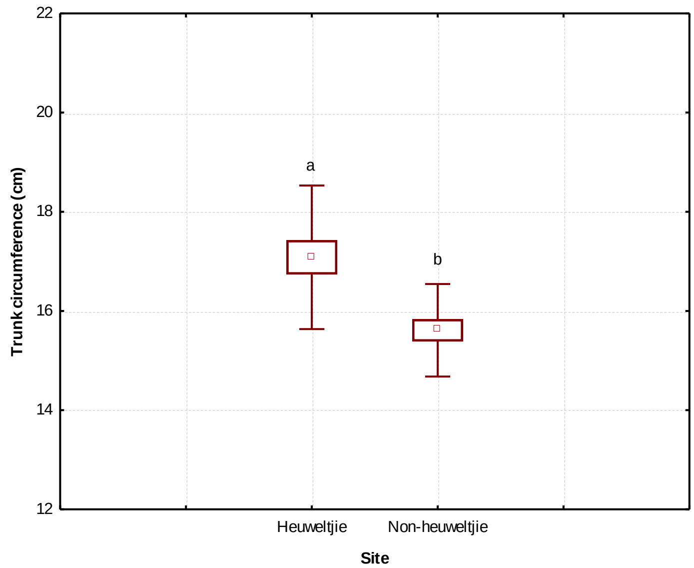

Figure 4.14: Trunk circumference of the grapevines growing on and off heuweltjie soils in the Stellenbosch study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different ($p > 0.05$; paired t-test).

<u>3.1.4.2 Robertson</u>

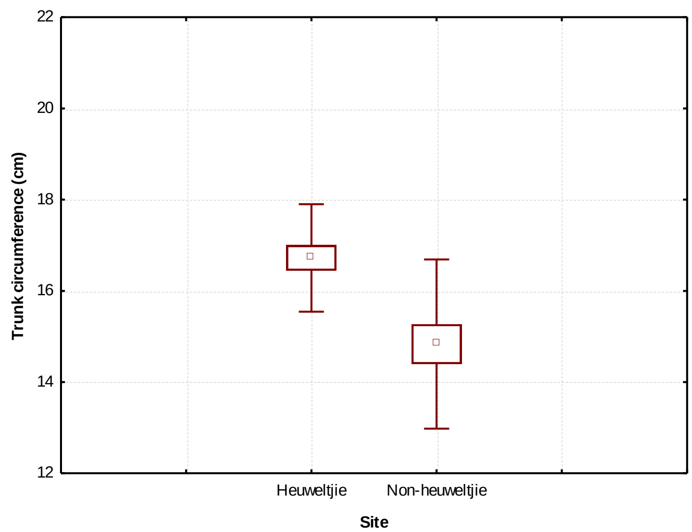

Figure 4.15: Trunk circumference of the grapevines growing on and off heuweltjie soils in the Robertson study area. The middle point represents the mean, the box the standard error and the whisker the standard deviation. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area.

The overall average of the trunk circumference was lower in the Robertson study area when compared to Stellenbosch. This is attributed to the different cultivars. Shiraz in Robertson has a smaller trunk circumference than Cabernet Sauvignon cultivated in the Stellenbosch study area. Vines associated with the heuweltjies exhibited significantly larger trunk circumferences than the non-heuweltjie vines ($p < 0.05$). The average value on the heuweltjie is 16.7 cm comparing to the 14.8 cm on the non-heuweltjie plots. The values range from 12.0 cm on H4O to 19.0 cm on H2C.

3.1.5 Pruning mass

3.1.5.1 Stellenbosch

Measurement of a grapevine's pruning mass is a good indicator of vine vigour (A. Strever, Senior lecturer Viticulture, U.S., 2010, personal communication). Upon investigation of the pruning results, it is clear that major differences exist between the vigour of the grapevines growing on and off heuweltjies (Table 4.4). Main shoots, water shoots as well as lateral shoots seem to benefit from the altered soil characteristics found on the heuweltjies, in terms of quantity as well as mass, though significant differences only emerged when comparing lateral shoots ($p < 0.05$). The differences in shoot quantity between heuweltjie and non-heuweltjie plots are most substantial in the laterals, with the heuweltjie vines comprising of almost nine shoots more per vine than corresponding non-heuweltjie vines, thus creating a denser canopy. Due to the faster growth and the increased length of the main shoots on the heuweltjies, the tipping action was started earlier which caused a stimulation of lateral shoot growth. This is the reason for the higher number as well as longer lateral shoots on the heuweltjie vines in comparison to the non-heuweltjie vines. This higher number of lateral shoots inevitably leads to a higher lateral shoot mass per vine. Heuweltjie vines also have on average 1.25 more main shoots per vine than non-heuweltjie vines with the mass of the total main shoots per vine on average being almost 500 g higher.

Table 4.4: Means (±SE) of the pruning results per vine, obtained from the pruning mass experiment in the Stellenbosch study area. Sites were compared using a paired t-test. n = 4; this value was arrived at after averaging the 12 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different ($p > 0.05$; paired t-test).

Plot	# Main shoots	Mass (g)	# Water shoots	Mass (g)	# Lateral shoots	Mass (g)	Total mass/vine (g)
On	17.06 (±0.37)a	1267.81 (±42.162)a	5.25 (±0.27)a	187.8125 (±11.33)a	25.5 (±3.17)a	493.19 (±137.92)a	1948.81 (±148.65)a
Off	15.8125 (±0.61)a	766.94 (±65.58)b	4.8125 (±0.65)a	115.25 (±13.78)a	16.75 (±2.81)b	192.38 (±28.15)a	1074.56 (±75.00)b

When the shoot mass measurements of the trial test followed, substantial differences were found in the detail of the vigour when heuweltjie and non-heuweltjie vines were compared. The results of the trial test clearly indicate that the vines on the heuweltjie follow a different growth pattern to those growing on the surrounding soil and substantial variations were distinguished in all of the aspects investigated, as clearly illustrated in Table 4.5.

Table 4.5: Means (±SE) of the results on the pruning mass of the grapevines associated with soils on and off the heuweltjies in the Stellenbosch study area (All main shoots were topped). n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

Plot	Main shoot mass (g)	Main shoot length (cm)	# Nodia	# Lateral shoots	Lateral Mass (g)	Lateral length (cm)	# Nodia
On	135.43 (±8.42)a	145.34 (±9.45)a	22.38 (±2.53)a	4.56± (0.62)a	80.64 (±18.42)a	193.77 (±32.37)a	59.06 (±11.73)a
Off	85.83 (±3.76)b	108.51 (±10.13)a	19.50 (±0.68)a	3.31 (±0.33)a	42.69 (±9.75)a	109.25 (±17.22)a	35.38 (±6.61)a

Growth was significantly altered and considerably more vigorous on the heuweltjie than on the surrounding soil. Main shoots associated with vines growing on heuweltjies was longer by an average of about 37 cm and a single main shoot weighed an average of 50 grams more than a main shoot on non-heuweltjie vines. This difference was significant ($p < 0.05$). The average total lateral shoot length per vine ammounted to approximately 84 cm longer on the heuweltjie vines than the non-heuweltjie vines, and respectively an average mass of 38 grams higher. There also seemed to be an average of 1.25 more lateral shoots per vine on the heuweltjies when compared to non-heuweltjie plots.

3.1.5.2 Robertson

The heuweltjie vines contain on average 1.88 less main shoots than the corresponding non-heuweltjie vines with the mass of the bunched main shoots being on average 289 grams lower respectively (Table 4.6).

Table 4.6: Means (±SE) of the results obtained from the pruning mass experiment in the Robertson study area (Majority of the lateral - and water shoots were already removed when pruning commenced and were not taken into account in this particular instance). Sites were compared using a paired t-test. n = 4; this value was arrived at after averaging the 12 vines for each heuweltjie and non-heuweltjie area.

Site	# Main shoots	Mass (g)	Total mass/vine (g)
On	13.06 (±1.20)a	610.00 (±48.08)a	610.00 (±48.08)a
Off	14.94 (±0.66)a	901.88 (±95.39)a	901.88 (±95.39)a

With the trial test (Table 4.7), the same general conclusion was made, and very few significant differences were found. The average main shoot length of a vine growing on a heuweltjie was 68 cm shorter and weighed 40 grams less than a non-heuweltjie vine. Nodia, which represents the potential new leaves, lateral shoots and bunches that could form on the main shoot, was significantly more off the heuweltjies than on. When the lateral shoot length was compared, it was once again found that the non-heuweltjie vines exhibited a trend of longer and heavier lateral shoots than the heuweltjie vines. The total lateral shoot length of the vines subjected to the trial test amounted to an average of about 35 cm shorter on the heuweltjie than off the heuweltjie. The mass of the lateral shoots were very similar, which suggests that lateral shoots on vines associated with heuweltjies are smaller in diameter when compared to non-heuweltjie vines in the Robertson study area.

Table 4.7: Means (±SE) of the results obtained from the test trial done on the pruning mass of the grapevines associated with soils on and off the heuweltjies in the Robertson study area (All main shoots were topped). n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

Site	Main shoot mass (g)	Main shoot length (cm)	# Nodia	# Lateral shoots	Lateral length (cm)	# Nodia	Lateral Mass (g)
On	89.86 (±2.04)a	152.94 (±16.40)a	19.88 (±3.09)a	2.50 (±0.00)a	108.89 (±15.75)a	19.88 (±2.23)a	25.48 (±2.08)a
Off	129.84 (±18.97)a	220.61 (±15.61) a	31.38 (±4.19)b	2.69 (±0.21)a	143.43 (±13.18a)	32.56 (±2.28)a	28.28 (±5.14)a

3.2 Berry analysis

3.2.1 Stellenbosch

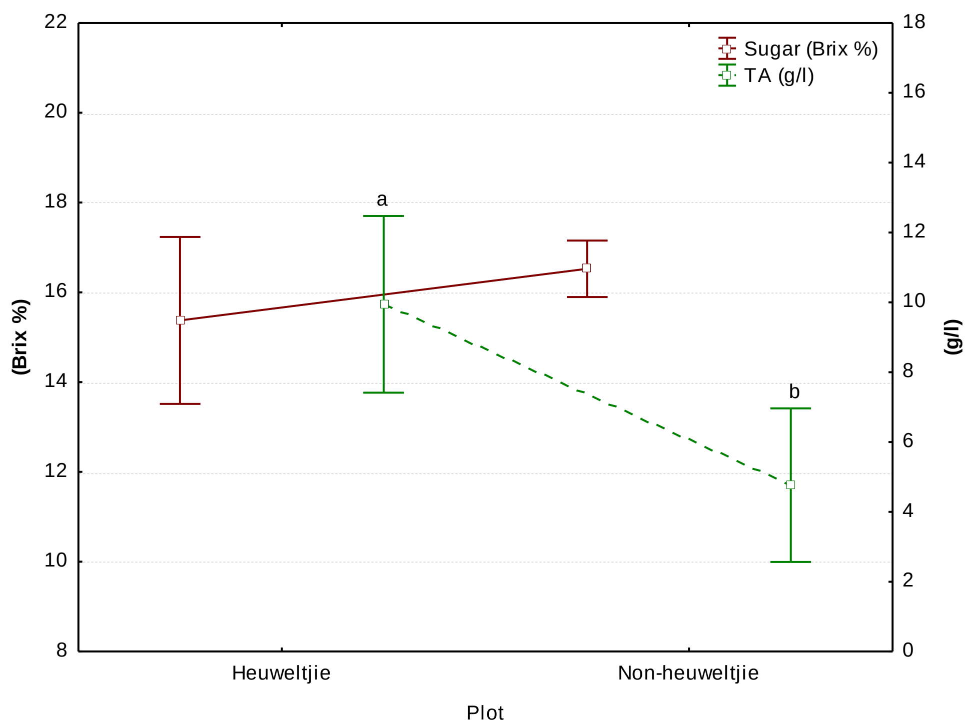

Figure 4.16: Berry sugar and titratable acid (TA) contents from the vines growing on and off the heuweltjies in the Stellenbosch study area, two months before harvest. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. Within each parameter means with different letters are significantly different (p < 0.05; paired t-test).

It was found that the sugar content of the berries growing on the heuweltjie was on average only one Brix unit lower in comparison to its adjacent soil, while the titratable acididity (TA) was significantly higher on the heuweltjie, indicating a slower maturation of the grape bunches on the heuweltjies.

3.2.2 Robertson

It seems here that maturation takes place more quickly on the heuweltjie than off the heuweltjie, as indicated by the higher sugar content of the berries. The TA of the berries associated with the heuweltjies, on the other hand was lower when compared to the berries growing off the heuweltjies.

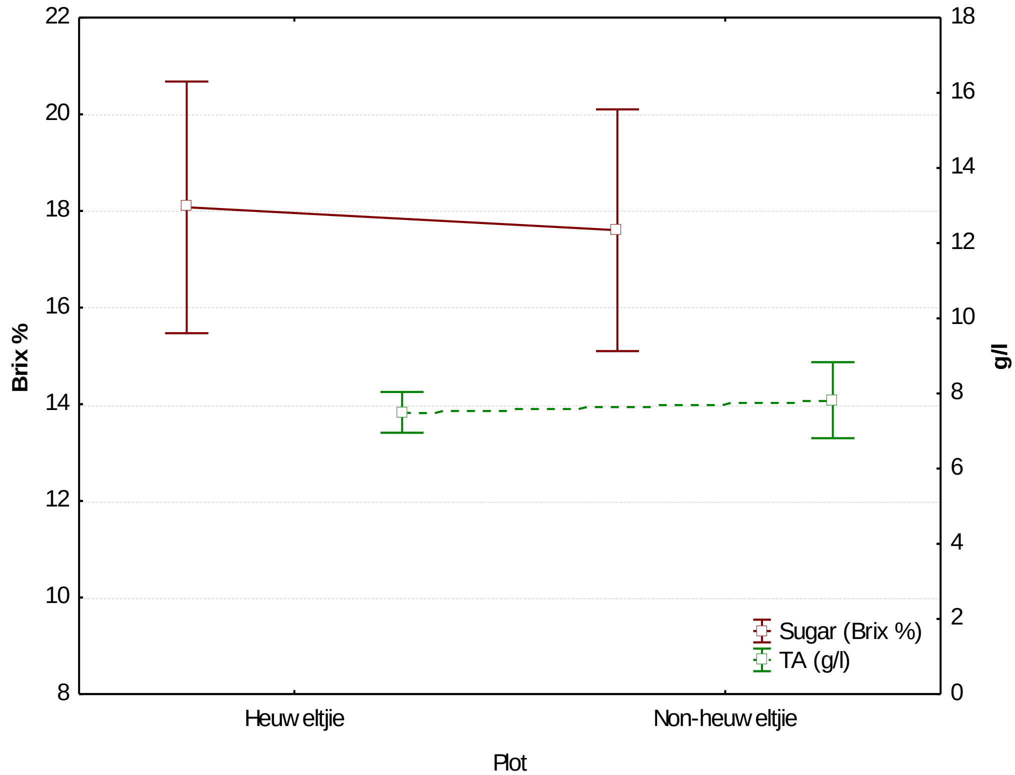

Figure 4.17: Berry sugar and titratable acid (TA) contents from the vines growing on and off the heuweltjies in the Robertson study area, one month before harvest. n = 4; this value was arrived at after averaging the 4 vines for each heuweltjie and non-heuweltjie area. No significant differences were found ($p > 0.05$; paired t-test).

3.3 Wine

3.3.1 Wine chemical analysis

3.3.1.1 Stellenbosch

Heuweltjie wines displayed reduced sugar levels and an increase both in titratable and malic acid concentration when compared with non-heuweltjie wines. Average malic acid values of 3.76 and 4.57 g/l, average titratable acidity of 5.87 and 5.29 g/l and average fructose values of 0.61 and 1.11 g/l were found in wines emanating from heuweltjie and non-heuweltjie wines respectively. The alcohol percentage was also much lower for the wines emanating from the heuweltjie plots when compared to non-heuweltjie plots, with an average ethanol percentage of 14.11 and 16.11 %, and average glycerol percentage of 11.58 and 12.22 % respectively. All results listed here rendered significant differences between heuweltjie and non-heuweltjie plots ($P < 0.05$). No significant differences could be discerned in the volatile acid, lactic acid and glucose contents between the heuweltjie and non-heuweltjie wines ($P > 0.05$). All results are displayed in Table 4.8.

Table 4.8: Means (±SE) of the sampled wine chemical properties of the wines produced from the grapes emanating from the Stellenbosch study area, as well as the commercially produced wines (EE), as analyzed by the Winescan. n = 4. Means followed by the same letter are not significantly different ($p > 0.05$; paired t-test).

Plot	Ethanol (% v/v)	Titratable acidity (g/L)	Volatile acid g/L	Lactic acid (g/L)	Malic acid (g/L)	pH	Glycerol (g/L)	Fructose (g/L)	Glucose (g/L)
On	14.11 (±0.24)a	5.87 (±0.04)a	0.20 (±0.06)a	<0.3a	4.57 (±0.07)a	3.70 (±0.02)a	11.58 (±0.07)a	0.61 (±0.06)a	<0.3a
Off	16.12 (±0.15b	5.29 (±0.06)b	0.26 (±0.02)a	<0.3a	3.76 (±0.10)b	3.80 (±0.02)b	12.23 (±0.15)b	1.11 (±0.03)b	<0.3a
EE On	***16.54***	***4.54***	***0.34***	***0.8***	***1.03***	***3.83***	***14.08***	***1.69***	***0.34***
EE Off	***16.12***	***4.54***	***0.47***	***0.31***	***1.03***	***3.77***	***14.74***	***1.33***	***2.14***

3.3.1.2 Robertson

Wine was made from the vines of only three sites in the Robertson study area, due to financial limitations. The pH and fructose exhibited lower values in the heuweltjie plots than the non-heuweltjie plots, while the glycerol displayed an opposite pattern, exhibiting higher values on the heuweltjie in comparison with non-heuweltjie plots. However, results proved to be insignificant ($p > 0.05$) and no conclusions could be made based on the findings. All results are displayed in Table 4.9.

Table 4.9: Means (±SE) of the sampled wine chemical properties of the wines produced from the grapes emanating from the Robertson study area, as analyzed by the Winescan. n = 3. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

Plot	Ethanol (% v/v)	Titratable acidity (g/L)	Volatile acid g/L	Lactic acid (g/L)	Malic acid (g/L)	pH	Glycerol (g/L)	Fructose (g/L)	Glucose (g/L)
On	14.42 (±0.73)a	4.91 (±0.14)a	0.37 (±0.06)a	<0.3a	3.47 (±0.2)a	3.7 (±0.02)a	11.03 (±0.31)a	0.65 (±0.07)a	<0.3a
Off	14.26 (±0.74)a	4.72 (±0.13)a	0.43 (±0.05)a	<0.3a	3.48 (±0.09)a	3.8 (±0.05)a	10.66 (±0.2)a	0.77 (±0.1)a	<0.3a

3.3.2 Wine sensory analysis

3.3.2.1 Stellenbosch

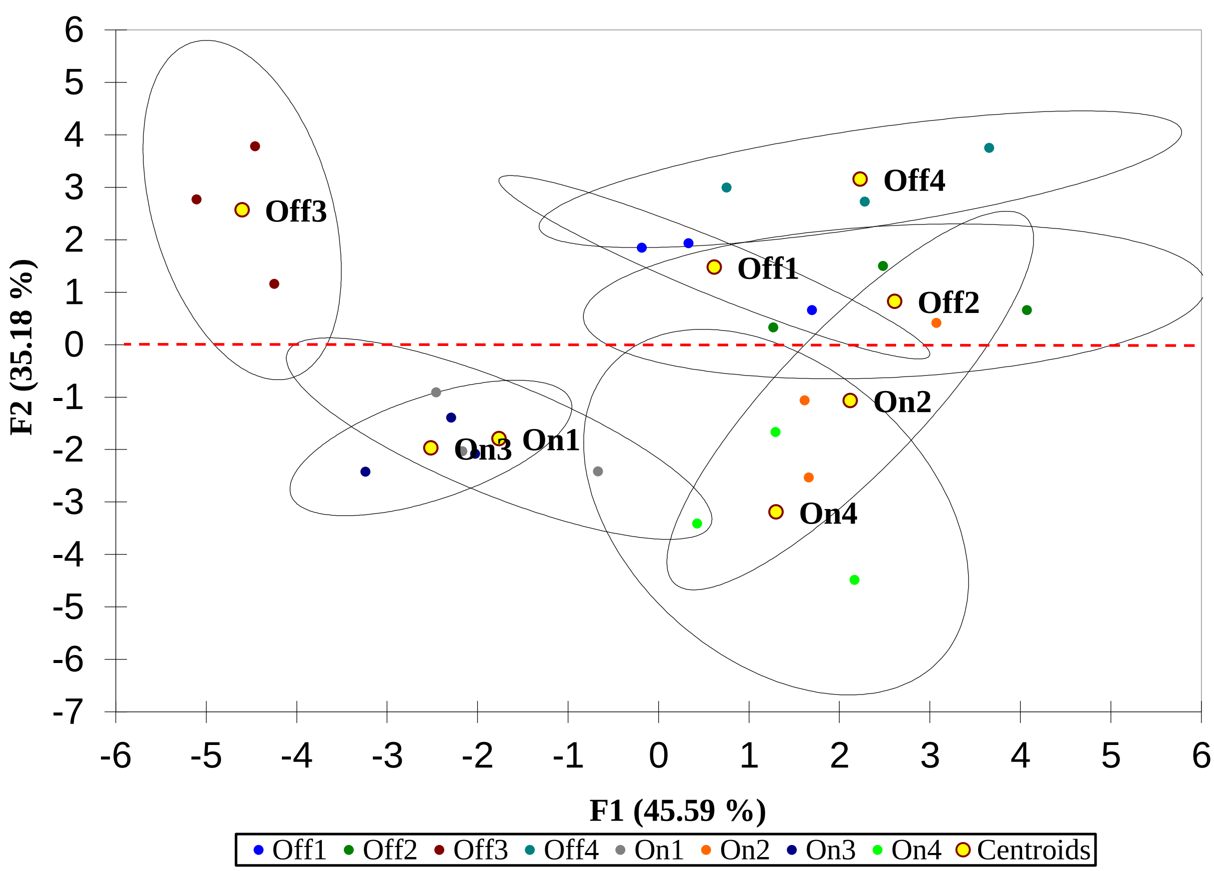

Figure 4.18: Descriptive analysis plot of sensory attributes of Cabernet Sauvignon wines produced from four heuweltjie and non-heuweltjie plots in the Stellenbosch study area.

A very distinct pattern is observed upon analysis of the wines emanating from the Stellenbosch study area. According to Factor 1 (Figure 4.18), which explains 45.59% of the variation, Off3 wine is significantly different from the rest of the wines. This could be due to differences in vigour of the vines associated with the Off3 plot. However, Factor 2 which explains 35.18% of the variation shows that it is apparent that wines produced from the heuweltjie plots are significantly different when compared to the non-heuweltjie wines, as shown by its distribution above and below the red line in Figure 4.18. There is also a clear indication that similarities exist between the wines emanating from the heuweltjie plots, as well as between the wines emanating from the non-heuweltjie plots. Where the oval shapes surrounding the different sample wines overlap, they share characteristics.

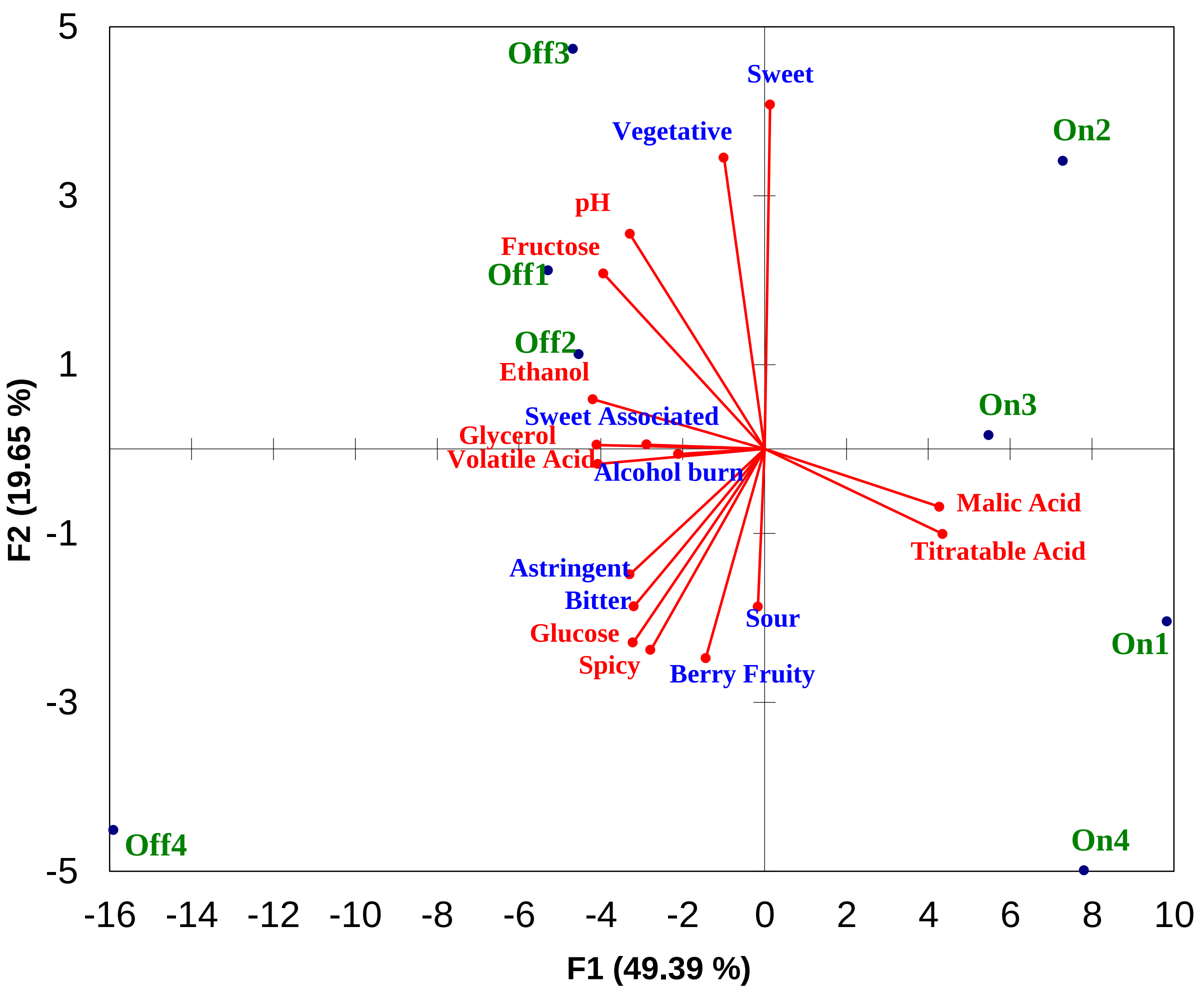

Figure 4.19: Principle component analysis bi-plot with scores (On and Off-plots) and loadings (chemical together with sensory attributes) of Cabernet Sauvignon wines produced from four heuweltjie and – non-heuweltjie plots in the Stellenbosch study area.

Figure 4.19 illustrates that in terms of specific chemical and sensory attributes, the heuweltjie plots lie completely on one end of the spectrum, while the non-heuweltjie plots lie on the opposite side. The different heuweltjie wines display very similar sensory attributes, but is mostly characterized by its high concentration in malic and titratable acid (as also shown in the wine chemical results). On2 and On3 exhibit small hints of sweet and vegetative characters, while On1 and On 4 exhibit a more berry-fruity, sour, bitter and astringent character. No specific sensory attribute is highlighted in heuweltjie wines and it is considered "more mild and bland" than the non-heuweltjie wines. In view of the non-heuweltjie plots, much less variation is detected within the plots, except in the case of Off4. Off1, Off2 and Off3 all seem to exhibit the same sensory attributes such as vegetative, sweet associated and alcohol burn. Off4 is significantly different compared to the other Off-plots and displays a more astringent, bitter, sour and berry-fruity character. The main difference between the heuweltjie and non-heuweltjie plots is that all of the sensory attributes is significantly heightened in the Off-plots. The On-plots show far less distinctiveness in terms of sensory attributes and wines with less features is the result. The only significant difference ($p < 0.05$) between the heuweltjie and non-heuweltjie wines is found in the astringency and the alcohol burn, being higher in the heuweltjie wines (Table 4.10).

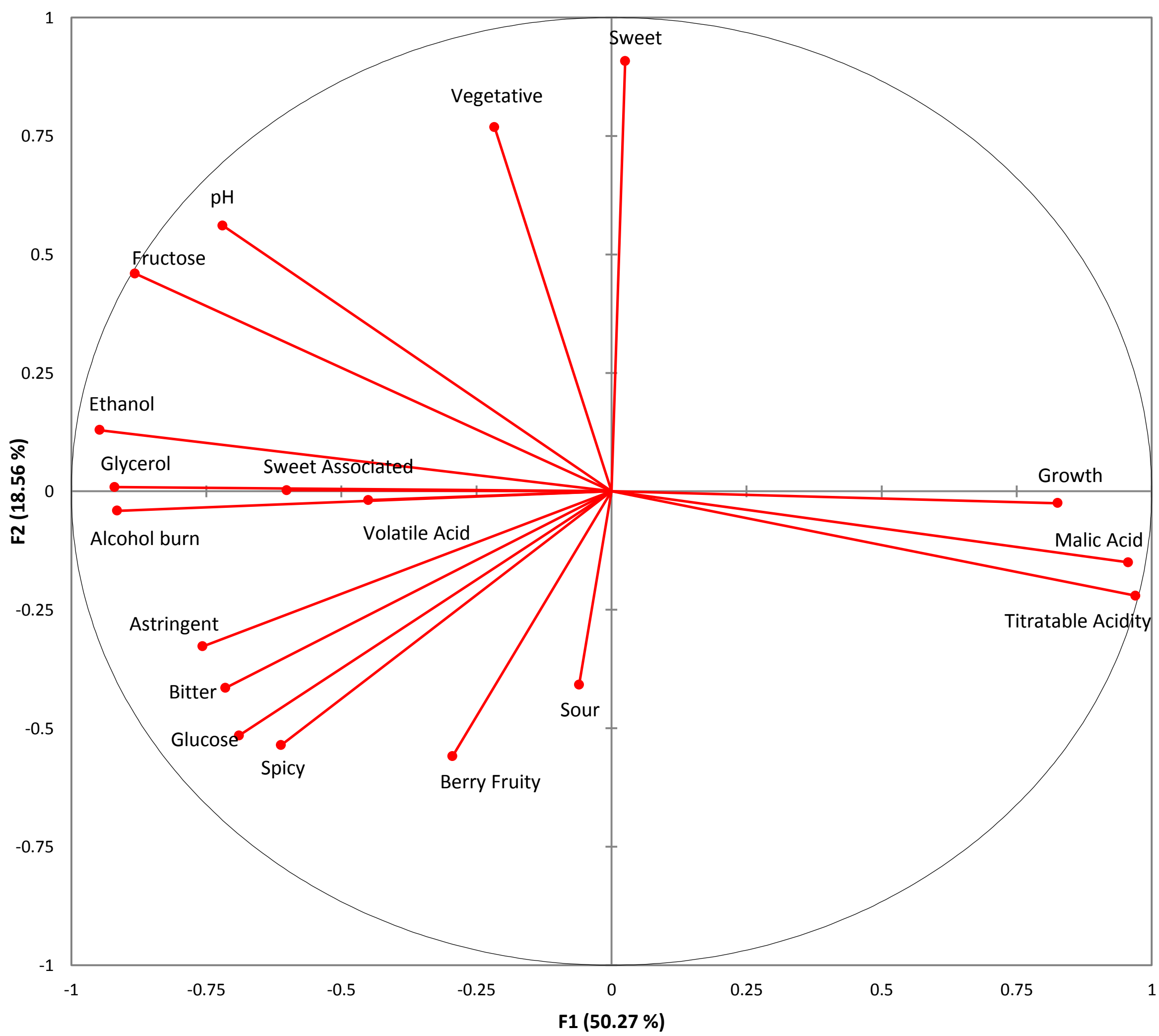

Figure 4.20: Principle Component Analysis plot displaying the distribution of variables (chemical - together with sensory - and growth attributes) of Cabernet Sauvignon wines and vines produced from four heuweltjie and – non-heuweltjie plots in the Stellenbosch study area.

A very interesting, yet significant relationship could be discerned between the wine quality and growth of the associated vines. These growth characteristics of the vines are a factor undoubtedly influencing wine chemical attributes such as malic and titratable acids (clearly depicted in Figure 4.20), thus also establishing it as a causal factor for the occurrence of certain specific sensory attributes. This can also have significant repercussions for sensory attributes such as general fruitiness and vegetative character. Attributes such as the vegetative character found in wines is normally associated with a more vigorous growing vine and it could be hypothesized that, by simply examining the growth characteristics and pruning mass data per plot, an estimate can be made of what sensory attributes can be expected. Differentiation in vineyard growth tends to induce major microclimate diversity, even within the boundaries of a vineyard block, thus differences in wine quality is bound to occur.

Table 4.10: Means (±SE) of the sensory attributes of Cabernet Sauvignon wines emanating from four heuweltjie (On) and four non-heuweltjie plots (Off) in the Stellenbosch study area. n =4. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

	Aroma				Palate				
Plot	**Berry Fruity**	**Vegetative**	**Sweet Associated**	**Spicy**	**Sweet**	**Sour**	**Bitter**	**Astrin-gency**	**Alcohol burn**
On	51.2 (±1.66)a	12.27 (±2.74)a	35.5 (±0.96)a	11.11 (±1.82)a	30.32 (±1.09)a	38.4 (±1.51)a	5.23 (±0.65)a	42.92 (±2.1)a	17.17 (±0.46)a
Off	51.91 (±1.12)a	14.46 (±0.68)a	37.83 (±1.63)a	14.35 (±1.51)a	31.27 (±1.23)a	37.85 (±2.46)a	7.98 (±1.86)a	49.29 (±2.33)b	19.73 (±0.41)b

3.3.2.2 Robertson

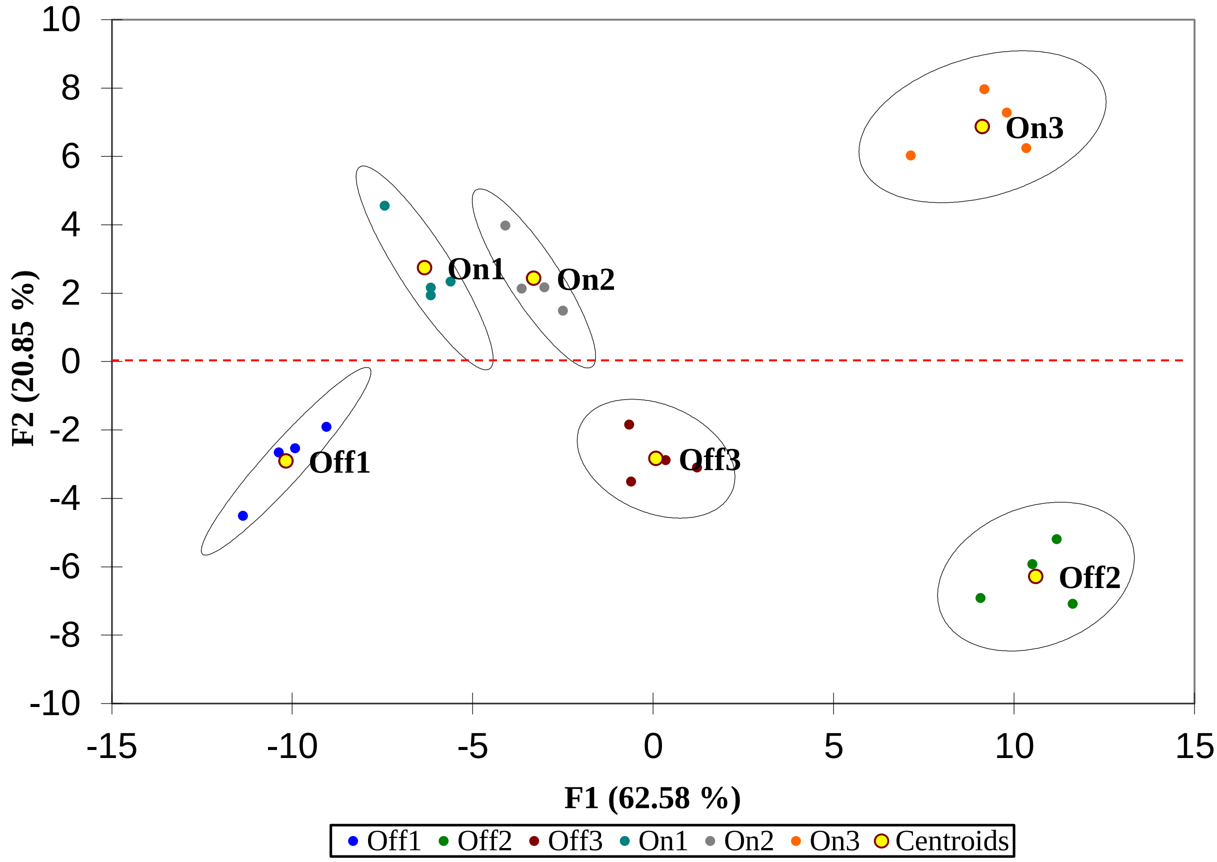

Figure 4.21: Descriptive analysis plot of sensory attributes of Shiraz wines produced from three heuweltjie and non-heuweltjie plots in the Robertson study area.

Overall differences in wine sensory attributes were less distinctive for the wines in the Robertson study area. According to Factor 1, it is clear that wines from the On-plots differ considerably from those of the Off-plots as shown by its distribution above and below the red line in Figure 4.21. It is also apparent that the two heuweltjie plots, On1 and On2 are very similar with regard to sensory attributes of the respective wines produced from these sites. However, the sensory attributes of the wine produced from On3 is unrelated to On1 and On2.

According to the PCA bi-plot on the sensory attributes (Figure 4.22) of the wine produced from On3, it has a fruity flavour, a reasonable sweet taste and is relatively low in acidity. It is also clear that On3 is very high in volatile acids (a negative attribute for wine) which can be the cause for the different wine sensory attributes when compared to On1 and On2.

The wine produced from site Off2 is dissimilar to that of the other Off-plots and is clearly illustrated in both Figures 4.21 and 4.22. It can be deduced, be examining Figure 4.22 and Table 4.12, that the wine produced from location Off2 had a strong savoury flavour, an aroma that was savoury-like and slightly vinegary and a reasonably high degree of astringency. The wine produced from Off2 had the highest pH, percentage ethanol and fructose content. The only significant difference ($p < 0.05$) between the heuweltjie and non-heuweltjie wines is found in the fruitiness, being higher in the non-heuweltjie wines.

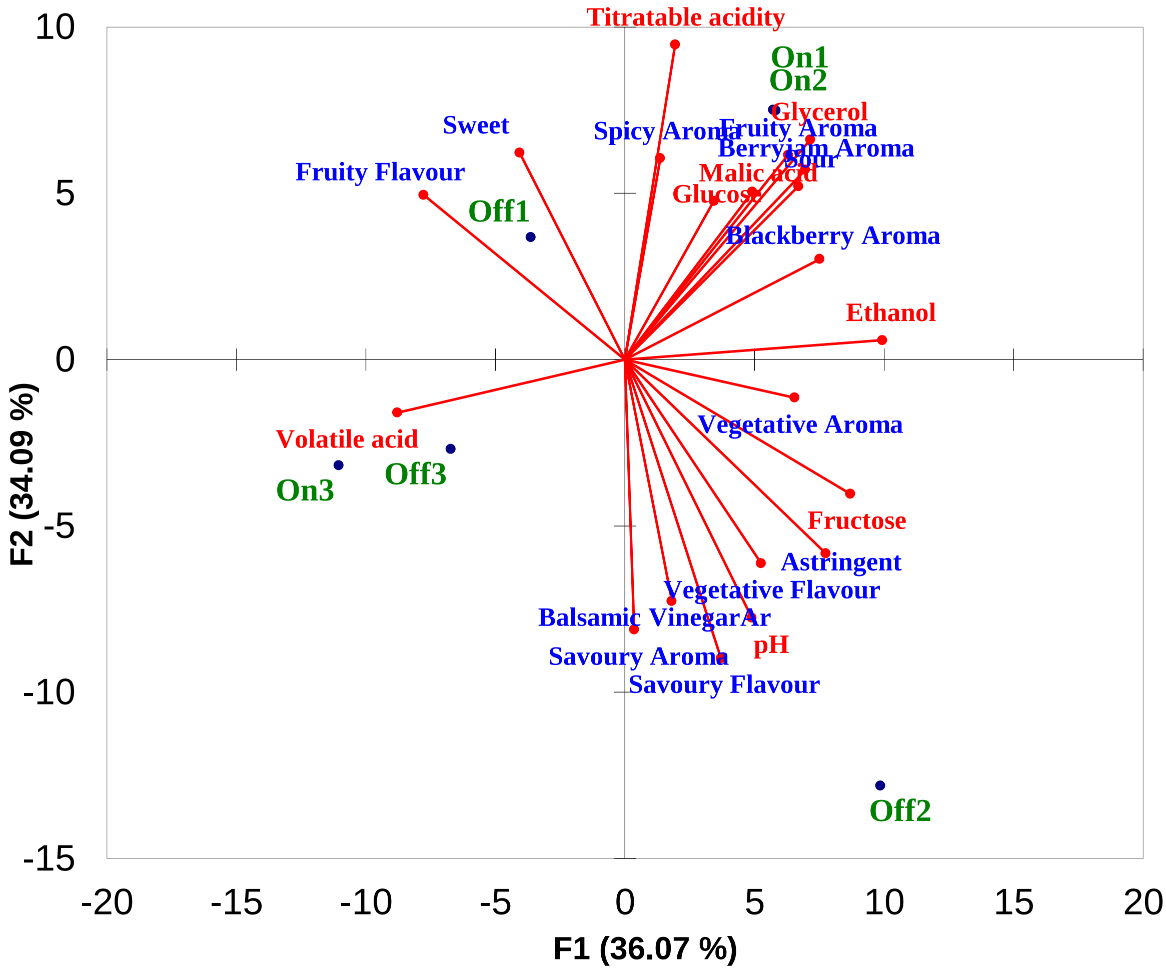

Figure 4.22: Principal component analysis bi-plot with scores (On and Off-plots) and loadings (chemical together with sensory attributes) of Shiraz wines produced from three heuweltjie and non-heuweltjie plots in the Robertson study area.

According to Figure 4.23, depicting the relationship between the chemical, sensory and growth attributes of the Shiraz emanating from the heuweltjie and non-heuweltjie areas in the Robertson study area, no particular association can be discerned between these attributes. Growth is correlated to attributes such as fruity flavour and sweetness, as well as with balsamic vinegar and savoury aroma.

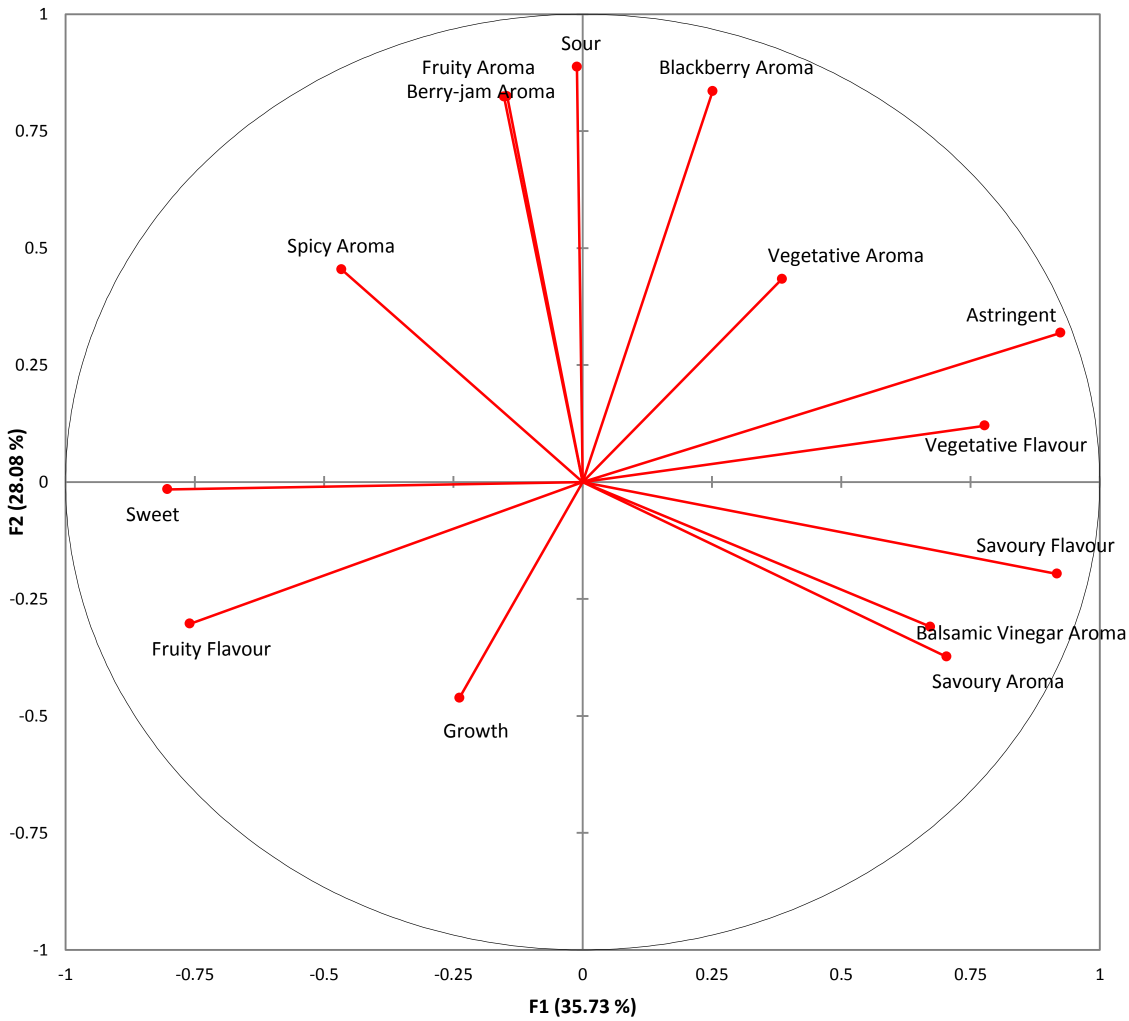

Figure 4.23: PCA plot displaying the distribution of variables (chemical together with sensory and growth attributes) of Shiraz wines and vines produced from three heuweltjie and non-heuweltjie plots in the Robertson study area.

Table 4.11: Means (±SE) of the sensory attributes of Shiraz wines emanating from three heuweltjie (On) and three non-heuweltjie plots (Off) in the Robertson study area. n =3. Means followed by the same letter are not significantly different (p > 0.05; paired t-test).

	Aroma							Palate					
Plot	**Fruity**	**Berry Jam**	**Blackberry**	**Vegetative**	**Savoury**	**Spicy**	**Balsamic Vinegar**	**Fruity**	**Vegetative**	**Savoury**	**Sweet Taste**	**Sour Taste**	**Astringency**
On	47.59 (±2.8)a	23.14 (±5.16)a	13.05 (±1.33)a	24.65 (±1.54)a	19.85 (±1.64)a	3.61 (±0.74)a	2.81 (±1.24)a	44.02 (±0.62) a	25.48 (±0.63)a	16.19 (±0.45)a	25.42 (±0.66)a	33.3 (±1.40)a	35.15 (±0.81)a
Off	45.03 (±2.77)b	23.67 (±2.10)a	9.17 (±1.61)a	25.77 (±0.78)a	21.48 (±2.12)a	3.47 (±0.60)a	5.11 (±1.73)a	42.49 (±0.81) a	26.78 (±2.10)a	17.97 (±1.32)a	25.65 (±1.64)a	30.92 (±0.58)a	35.78 (±3.15)a

Table 4.11 depicts the mean values for the respective sensory attributes and the significant differences between the respective plots. Through the integration of chemical and sensory data, it is possible to indicate specific correlations between the wine's chemistry and sensory attributes

4. DISCUSSION

The results presents measurements of ecophysiological properties and measurements of vigour of vines growing on and off heuweltjies in the Stellenbosch (Fynbos Biome) and Robertson (Succulent Karoo Biome) wine growing regions. These measurements were augmented by analyses of berry and wine characteristics. In general, little difference was found in ecophysiological measurements on and off heuweltjies, despite differences in water availability on and off heuweltjies (see Chapter 3). Measurements of vigour on the heuweltjies, however, showed significant deviations from the non-heuweltjie plots, which seem to be related to soil characteristics (hydrology and chemistry). Also, some differences were found in berry characteristics in Stellenbosch (Cabernet Sauvignon), notably in titratable acid content, but no such differences were found at the drier site (Shiraz). However, these differences in acidity and associated measures were also carried over into the wines that were produced from the Stellenbosch study area, and this seemed to be related to canopy characteristics (higher leaf density on the heuweltjies at Stellenbosch).

4.1 Plant physiology

4.1.1 Stomatal conductance

Stomatal conductance provides an integrated evaluation of the intensity of water stress experienced by a specific plant (Lambers *et al.*, 1998; Flexas *et al.*, 2002). Therefore, any increase in stomatal conductance following rainfall or irrigation in a vineyard is a clear indication of a recovery of water status. At Stellenbosch trends show higher stomatal conductance on heuweltjies as opposed to the non-heuweltjie areas (significant in March, at the end of the dry season), an indication that water may be more available in the termite-affected soil. This confirms our earlier results where higher water contents were found in the soils on the heuweltjies in comparison to soils surrounding the heuweltjies. Thus, our initial expectation that higher water availability on the heuweltjies in Stellenbosch would lead to higher stomatal conductance was confirmed; the stomata are more open and active on the heuweltjie. The loss of water through the stomata by means of transpiration therefore is much higher, as water is abundant in the heuweltjie soil. This again emphasizes the fact that vines grown on heuweltjie soils are less prone to water stress.

Stomatal conductance values can be influenced by variable weather conditions and vineyard management practices (Cifre *et al.*, 2005). It is directly proportional to the amount of sunlight radiation received by the leaves. If skies are clear, the stomata will be more open which in turn gives rise to a higher photosynthetic tempo. The cause for the low values in the month of February was the overcast conditions prevailing on the day of measurement. Stomata close up when sunlight radiation decrease, which retards transpiration and prevent excessive water loss (Lambers *et al.*, 1998). The amount of sunlight and clouds significantly affect the stomatal conductance value obtained. As the weather conditions, more specifically sunlight radiation, varied with every reading, stomatal conductance values changed accordingly. With temperatures soaring while measurements were taken, the vines close up its stomata and switch to ‘stress mode’. This defence mechanism of plants kicks in when there is a shortage in available water, so that water is used more sparingly and efficiently. With variable temperatures, cloud cover, wind and water availability, actual values of stomatal conductance could therefore only be compared between heuweltjie and non-heuweltjie plots and not between the different months of measurement. It is also worth mentioning that the vineyard in the Stellenbosch study area was subjected to extreme winds in December and January that caused damage to a large percentage of the leaves and shoots. The utmost was tried to do experiments only on strong, healthy leaves situated in the bunch zone, but it was not always possible. Results could therefore have been influenced.

Management practices like irrigation can also influence stomatal conductance (Cifre *et al.*, 2005). High evaporative demand during dry periods can cause the incidence of embolisms, thus giving rise to a decrease in conductance capacity of stems and petioles, and xylem disfunction (Lovisolo and Schubert 1998; Schultz, 2003). Vineyard managers try to minimize stress during certain critical growth periods by irrigation, where such a facility is available. The Robertson region is significantly drier than Stellenbosch, and irrigation is therefore more important. Thoughout the study period the Robertson plots were irrigated more frequently. This may be the reason why we found little differences in stomatal conductance on and off heuweltjies in Robertson. We expected to find a trend towards higher stomatal conductance off the heuweltjie, which is in accordance with lower water availability on the heuweltjies due to the physical and chemical characteristics of the soil. However, due to the damage caused by the hail in the month of February, results are inconclusive and data for three months are far too little to produce significant results and comparisons. Results would prove more feasible if further repetition was implemented, especially later in the season when drier conditions normally prevail.

4.1.2 Leaf water potential

Assessment of plant water status regarding irrigation scheduling is critical when spatial heterogeneity is taken into account. Leaf water potential is directly correlated to plant water stress and it was initially speculated that a much lower reading would be obtained from the vines growing on the heuweltjies in comparison to vines growing off the heuweltjies. No significant trends were obtained, and variability was high throughout the measurement period. Trends in accordance with our expectations (higher leaf water potential on heuweltjies in Stellenbosch and lower in Robertson) were found, but were limited only to certain months. These trends were mainly detected during the hot, dry months when little or no rainfall occurred.

Leaf water potential indicates the level of water stress the plant experiences. While direct statistical comparisons between Stellenbosch and Robertson are not made, it is notable that generally lower water potentials are found at Stellenbosch. While predawn water potential is relatively low in December at Robertson, this situation changes considerably in January and February when the level of stress experienced by the plant was apparently very low (the Ψ_{max} values between 0 and -1 bar in Janaury and February). Similar to the stomatal conductance results, it is feasible that irrigation that was applied much more frequently in Robertson, is heavily affecting the level of stress experienced by the plant. In Stellenbosch, the more mesic wine growing area, during the measurement period, irrigation was used much less, and Ψ_{max} values were concomitantly lower.

Midday water potentials integrate water stress produced by the combination of weather conditions, soil water content and other soil characteristics as well as management practices such as irrigation. At Robertson, with progressive aridity later in the season, Ψ_{min} values were lower than at Stellenbosch, despite more frequent irrigation. This is an indication that these vines are experiencing stress during the day, when stomatal conductance is high and the plant transpires at its maximum. However, perhaps due to irrigation, the vines are able to resuscitate during the night, and utilize the residual soil water, which may explain the high Ψ_{max} values.

By using either leaf or stem water potential readings as a function of vapour pressure deficit at time of measurement, a fully irrigated baseline was developed for grapevines (Williams and Baeza, 2007). Williams and Araujo (2002) as well as Williams and Trout (2005) found that both leaf and stem water potential correlated well with soil water content, soil matric potential and measurements of leaf gas exchange. In experiments with Thompson Seedless table grapes, a high correlation was found between values of leaf water potential, stomatal conductance and crop water stress index (Grimes and Williams, 1990). Thus, while no significant differences were found on and off heuweltjies in Ψ_{max} and Ψ_{min} values, we expect that these differences may well manifest under dryland conditions. Climatic factors that include rainfall and temperature could also play a major part in the grapevine's water relations and it is only when these factors are integrated together with the termite induced changes in soil characteristics that one may find vine water relations to be altered on the heuweltjie, in accordance with altered soil water conditions.

4.1.3 Canopy density

Vine balance is the culmination of a few very important factors, which includes the environment, variety and management. It is not only the topography that brings about environmental variation, but also patchiness of soil fertility and water-holding capacity (Gladstones, 1992), and what better way to emphasize such diversity than through the occurrence of heuweltjies. It must be the main aim of the viticulturist to recognize this variation and to initiate a management plan to overcome (if necessary) any obstacles that this new challenge will bring to the table.

It is important that vegetative vigour and fruiting load are in equilibrium, as well as of optimum quality. If the fruiting load is too heavy it will result in a delay in ripening coupled with a decrease in fruit quality and weakening of the vine (Gladstones, 1992). Two extremes of vine growth can be distinguished; excessive vegetative growth that leads to low quality fruit and inadequate growth that which produces low and uneconomic yields. Thus it is necessary to reach a balance between extreme or insufficient growth to achieve a kind of equilibrium. Shange *et al.* (2006) showed how increased vigour on heuweltjies can disrupt the balance of the grapevine, possibly to the detriment of berry and wine quality.

In the current study, in the Stellenbosch study area, the higher water content of the heuweltjie soils in comparison to the surrounding soils will have a major influence on the variation in soil temperature between heuweltjie and non-heuweltjie plots (A. Strever, Senior lecturer Viticulture, U.S., 2010, personal communication). At the start of the growing season, soil temperature is the main soil factor that influences budburst and growth. Due to its higher water content, the heuweltjie soils will have a slightly lower temperature when compared to the surrounding soils.

Therefore budburst will be delayed on heuweltjies due to higher soil water contents and lower soil temperatures. This was found to be exactly the case in Stellenbosch, with a significant delay in time of budburst as illustrated by Figure 4.11. As the growing season progresses, water is gradually withdrawn from the soil through absorption by the vine's root system, evaporation and desiccation, and therefore becomes the limiting property that replaces soil temperature as the main factor influencing vine growth. As the heuweltjie contains more water for a longer period of time than the surrounding soils, the growth of the vine tend to be more vigorous on the heuweltjies than on the adjacent surrounding soils. Similar results were found by Shange *et al.* (2006), also in the Stellenbosch region. Coupled with this increase in vine vigour is the decrease in canopy temperature as well as an increase in humidity, ultimately creating an ideal environment for disease outbreak, e.g. powdery mildew (Carrol and Wilcox, 2003). Also, due to the much lower percentage of light reaching the inside of the canopy of the heuweltjie vines, a very low effective leaf exposure is experienced on the heuweltjies. The bunch zone is almost entirely covered in shadow and its development will be severely inhibited, which in turn will have a detrimental effect on fruit and wine quality (Shange *et al.*, 2006).

Excessive vegetative growth takes place when the growing point of the shoots becomes too strong in demand for photosynthetic products so that the other organs obtain much less nutrients than required for growth and development. Vegetative growth and bunch development is in competition with each other for photosynthetic products. This competition begins during the initial growth in October and if it benefits shoot growth, reproductive growth will be impaired from flowering in November right through to fruit ripening in February/March. The extent to which bunch development is impaired is dependant on the strength of the demand by the shoot growing point and can vary from morphological deterioration (small, loose bunches) caused by strong competition, to chemical deterioration (low sugar – and high acid concentration) caused by moderate competition. When reproductive and vegetative growth is in balance, shoot elongation will end between véraison and ripening. This issue does not only cause problems in terms of competition for nutrients between shoot growth points and bunches, but also brings shading in the bunch zone of the canopy with detrimental consequences for fruit quality.

At Robertson we expected the opposite as found in Stellenbosch, namely that bud burst will begin earlier on the heuweltjies, and that canopy density will be lower due to water stress induced on heuweltjies. The damage caused by the unforeseen hail storm on 24/02/2010 in the Robertson study area, meant that canopy light measurements grinded to a halt before the bulk of the data were collected. During late summer, differences appeared, with vines on the heuweltjies showing higher light penetration due to more sparse shoot and leaf biomass. These differences may well have been more prominently displayed later in the season; however, we do not have the necessary data to back this up.

Earlier studies show the effects that vigorous growth and excessive shading has on the vine and its fruit includes delayed ripening with low sugar and high acid concentration (Smart, 1987), reduced yields (Smart, 1987), poor fruit quality (Rotem and Patti, 1969), low bud fruitfulness (Rotem and Patti, 1969) and higher incidence of disease

(Rotem and Patti, 1969). By studying the results of both study areas, it seems that the effect of heuweltjies on grapevines in terms of canopy density is totally opposite between sites. In Stellenbosch, a higher canopy density is perceived that lead to lower effective leaf exposure to sunlight. The opposite was true for Robertson, where higher canopy density was distinguished on the non-heuweltjie plots in comparison to the heuweltjie plots. Due to limited data, results obtained in the Robertson study area are inconclusive, however, the results optained suggest that the trends in vigour between heuweltjie and non-heuweltjie plots (as measured in terms of canopy density) may well have significant effects on berry and wine quality as suggested by Shange *et al.* (2006).

4.1.4 Trunk circumference

The results obtained from the trunk circumference measurements, showed a clear distinction between vines growing on and off the heuweltjies. It is quite apparent that the values are higher on the heuweltjie than off in both study areas. According to recent studies, there is a strong correlation between trunk circumference, soil texture and electromagnetic signatures that reflect differences in soil characteristics (Mills 2006, Imre *et al.* 2007, Trought *et al.* 2008).

The higher trunk circumference values of the vines associated with the heuweltjies corresponds to the finding earlier (Chapter 3) that the soils are more fertile on the heuweltjies. This ensures that a more suitable environment is created for vigorous growth. If the grapevine has free access to all its needs in terms of nutrients and water, higher vigour will be the result, and both sets of heuweltjies show this potential through higher trunk circumference, which is the reults of long term trends in growth. However, in the short to medium term, the more limited soil water availability and possibly the more stressfull growing conditions on the heuweltjies in Robertson gives rise to less vigorous growth in terms of shoots and leaves.

4.1.5 Pruning mass

The pruning mass of a grapevine is often considered to be an indicator of seasonal vegetative growth. Determination of the pruning mass of the grapevines on and off the heuweltjie allowed for a distinction in vigour, especially vegetative growth, between the different plots. An aspect that is closely linked to any given increase in pruning mass is the increase in the amount of new foliage that it brings forth. This factor is also associated with better a survival rate of leaf-feeding herbivores (Larsson and Smart 1988; Spiegel and Price 1996; Floater 1997).

Due to the higher water content of the heuweltjie soils in the Stellenbosch study area, the expectation was that a higher shoot length and mass should be observed on the heuweltjie plots than the non-heuweltjie plots. Upon the examination of the results obtained from the pruning experiments as well as the trial test, some of the initial speculations were justified and significant differences were observed in both the main shoot mass and number of lateral shoots between heuweltjie and non-heuweltjie plots. The total mass per vine was also significantly higher on than off the heuweltjie. Vine vigour is correlated to soil water content and any water that is applied through irrigation and received from rainfall will influence shoot length as well as leaf area in a positive way. This in turn will influence the amount of shade, humidity, temperature and the availability of young shoots (Daan and Williams, 2003).

The growth pattern of the vines on and off the heuweltjie in Robertson is the exact opposite from that of the Stellenbosch study area and the vines associated with the heuweltjie appears to grow less vigorously than the non-heuweltjie vines. Although results are insignificant, small differences in vigour are still apparent and alterations in growth are still very clear. Results of the trial test clearly indicate a significantly higher number of nodia on the main shoots of the non-heuweltjie vines then the heuweltjie vines. This is indicative of a greater potential for growth of the heuweltjie in this Karoo wine growing region. Even while nutrient content is significantly higher in the heuweltjie soils compared to non-heuweltjie soils, it seems that it is a less important control of vigour of the heuweltjies compared to water content.

4.2 Berry analysis

Results obtained from the berry analysis were quite conclusive and confirmed original hypotheses that berry characteristics, dynamics and quality would differ on and off heuweltjies. This indicates a major difference in the timing and duration of certain phenolic stadia of the vines growing on and off heuweltjies.

A canopy that grows more vigorously and dense than average, will have a heavier crop load relative to the actively photosynthesizing leaves (Smart and Robinson, 1991). This leads to a lower photosynthetic efficiency due to strong atmospheric saturation deficits, especially in mid-summer, through the closing of stomata earlier in the day. This reduces the sugar availability and accumulation during the ripening period which results in incomplete maturity in terms of sugar content. According to Sinton *et al.* (1978), simple over-cropping can also induce a decline in sugar accumulation. The result of this phenomenon will be a dilution of potassium in the fruit, which in turn decreases the pH of the berries. As colour, flavour and aroma compounds in the fruit are synthesized from the sugar surplus, retarded sugar flux will also cause the decrease in accumulation in these compounds and result in incomplete maturity in terms of colour, flavour and aroma (Gladstones, 1992).

In the Stellenbosch study area, the higher TA and lower sugar content of the heuweltjie berries indicate a delay in ripening of the vines on the heuweltjie and is most probably due to the lower degree of water stress the vine encounters on the heuweltjie. This causes the vine to export all its nutrients to vegetative growth in the leaves and shoots, very much to the detriment of the grape bunches in terms of sugar accumulation. The lower sugar content in combination with the higher TA of the grapes growing on the heuweltjie showed that less of the acid has been transformed into sugars. Thus, ripening and maturation of grape bunches on the heuweltjie was at a less advanced stage one month before harvest.

A different pattern emerges when results of the Robertson study area are examined as no differences were found between berries from the heuweltjie and non-heuweltjie areas. It must also be added that the differences in sugar content and TA on and off the heuweltjies are more apparent in the Stellenbosch study area than Robertson. The effects on berry and wine quality are therefore less pronounced in Robertson. It can be expected that more pronounced differences in vigour between heuweltjies and non-heuweltjie areas in the Robertson wine region with lower rainfall (more stressful conditions) would lead to differences in berry and wine quality.

Further studies were conducted in the Stellenbosch and Worcester area to indicate differences in grape composition related to excessive canopy shading (Archer, 2008). Grapes bunches from deep inside the canopy were compared to grapes grown on the outside of the canopy. Considerable differences were observed in sugar - and acid concentrations when the bunches were compared. The results of the study not only showed that shading by dense canopies has a detrimental effect on grape composition, but emphasized the fact that excessive vegetative growth coupled with dense canopy shading can induce uneven ripening in a vineyard. While grapes on the outside of the canopy already reached an optimal ripeness, the grapes on the inside of the canopy were still green. Therefore the average grape quality of such a vineyard will be lowered significantly if the grapes from the inside of the canopy are harvested with the grapes from the outside of the canopy.

The difference in berry characteristics will have a definite impact on cultivation practices as the phenological stadia vary considerably between heuweltjie and non-heuweltjie plots.

4.3 Wine

4.3.1 Wine chemical analysis

Due to the fact that the vines associated with the heuweltjies exhibited a more luxurious growth in Stellenbosch, véraison and ripening were delayed due to excessive shading within the canopy. This caused a significant decrease in the sugar content, particularly fructose, with increases in acidity, more specifically with higher concentrations in titratable and malic acid. In the Robertson study area, the opposite trend was expected for the wines obtained from the heuweltjie vines, as their canopies seemed to be less dense than that of the vines surrounding the heuweltjies. Here, variations between the wines made from heuweltjie vines and the wines emanating from the non-heuweltjie vines were small. The only noticeable trend that could be discerned was in the pH, glycerol and fructose values. Higher pH values and fructose concentrations were found in the heuweltjie wines, while the glycerol concentration were lower in comparison with non-heuweltjie wines, though in all cases this was insignificant at the 5% level.

We decided to aid Ernie Els Wines in their own trial by assisting in the separate harvesting of the heuweltjie and non-heuweltjie grapes from the Cabernet Sauvignon block on the farm. Heuweltjies were carefully marked off through the study of aerial photographs, leading to the separate harvesting of the heuweltjie and non-heuweltjie grapes. Subsequently, wines were also made separately and wine samples from Ernie Els Wines were used as a reference for our own wines. When these commercially produced wines are compared, wine chemical characteristics seem to be more or less similar on and off the heuweltjies, with an exception for glucose, which is approximately six times lower in the heuweltjie wine in comparison to the non-heuweltjie wine. This clearly supports the research on shading of bunches done by Smart (1982), who found a decrease in sugar, anthocyanin and phenol levels and increase in titratable and malic acid contents, but decrease in tartaric acid contents. He also found a higher pH and K content associated with the wines made from shaded canopies. Other studies display an herbaceous wine character (Pszczolkowski *et al.*, 1985) associated with excessive vegetative growth as well as a decline in aromatic compounds such as monoterpenes (Reynolds and Wardle, 1988).

According to the results obtained, a definite variation in wine-chemical properties can be observed between the wines emanating from heuweltjie and non-heuweltjie plots, though only in the high rainfall area. Although in some cases inconclusive, alcohol, sugar and acid percentages are all affected and/or affected by the presence of heuweltjies in vineyards. The results obtained in the Stellenbosch study area displayed the most substantial variation in above mentioned attributes, which raises further questions concerning the possible role that climate, and more specific rainfall, could play as a collaborator in such a scenario.

4.3.2 Wine sensory analysis

Wine quality is sometimes hard to label, but there seems to be consensus over which sensory characteristics are favourable. Colour, mouth-feel, flavour and aroma of wine are aspects of wine quality already extensively subjected to in-depth investigation (Peynaud and Ribéreau-Gayon, 1971; Sinton *et al.*, 1978; Smart 1987). Different treatments of Cabernet Sauvignon wines from the Stellenbosch study area and Shiraz wines from the Robertson study area were tested for a spectrum of sensory attributes using a trained panel and the technique of descriptive sensory analysis.

Since the wine sensory analysis concluded the study and shaped its climax, the results were very much imperative. Significant differences were found between the heuweltjie and non-heuweltjie wines in the Stellenbosch study area concerning its palate attributes, while in the Robertson study area certain aromatic differences were significant. On the heuweltjies in the Stellenbosch study area, the higher vine vigour led to more shaded bunches, therefore inducing higher acid concentrations and lower sugar concentrations (as indicated by the wine chemical analysis). This inevitably gave rise to complex sensory attributes when compared to non-heuweltjie wines. In Robertson, opposite observations were made concerning the shading of the canopy, with the heuweltjie-associated bunches being less shaded than non-heuweltjie bunches due to lower vine vigour of the vines on the heuweltjie. This again led to a display of different wine chemical and sensory characteristics, although not as distinct as Stellenbosch.

Past research indicate the impact of sunlight exclusion and shading of the bunches on Cabernet Sauvignon and Shiraz vines as well as their resultant wines (Downey *et al.*, 1994; Ristic *et al.,* 2007). In a study of the effect of shading on Cabernet Sauvignon, differences in anthocyanin and total phenolic levels were observed, but no distinction in wine flavour and aroma could be made between exposed and shaded bunches (Morrison and Noble, 1990). In another study on Shiraz, descriptive sensory analysis of the wines made from normally exposed and artificially shaded vines showed that wine emanating from shaded fruit exhibited lower fruit flavour and fruit flavour persistence, as well as lower astringency (Ristic *et al*., 2007). Shiraz's characteristic dark fruit flavour was less prominent in wines made from shaded fruit and mouthfeel characteristics rated lower (Smart, 1982).

It is difficult to describe wine flavour in terms of factors relating to soil properties due to the fact that changes in popularity over time and is both subjective and qualitative. The fact that wine sensory attributes varied so significantly between the heuweltjie and non-heuweltjie plots, could have extensive implications for wine quality, as wines emanating from heuweltjies exhibits a different wine style than that of the non-heuweltjie plots. The wine industry must undoubtedly pay heed to these findings and find a way to implement it into their management strategies. The high frequency of heuweltjies in Western Cape vineyards, immediately begs the question of implications for the wines emanating from such areas, most probably giving rise to altered wine quality and styles. This fact has recognized by the management team at Ernie Els Wines, who made commercial-scale wine from heuweltjie and non-heuweltjie wines, the results of which in terms of wine chemical attributes are used for a comparison in the current study.

5. CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this chapter were to determine the differences in vigour, physiology, berry and wine characteristics between the vines associated with heuweltjie and non-heuweltjie plots and to investigate the subsequent variation in wine quality that may follow. The implications for viticulture were also closely examined and it was concluded that certain specific aspects of management needed modification when heterogeneity of this degree is observed in a vineyard.

Upon assessment of the physiological characteristics, it is apparent that there were no major variation between the grapevines growing on and off the heuweltjie concerning stomatal conductance and leaf water potential. In the Stellenbosch study area, a higher stomatal conductance was observed on the vines associated with the heuweltjies. A higher average leaf water potential was also noted on these vines and it can be deduced that the vines associated with the heuweltjies in the Stellenbosch study area, are much less prone to exhibit water stress symptoms than vines growing on adjacent, non-heuweltjie soils, supporting results obtained from neutron water probe reading. An opposite result was obtained in the Robertson study area, with the stomatal conductance and leaf water potential measurements displaying lower values on the heuweltjie vines in comparison to the non-heuweltjie vines. Once again this correlated extremely well with the soil's water contents. Although these results are not as significant as first hypothesized, it can still be interpreted that the heuweltjies do have some influence on the vine physiology. These differences do however present substantial evidence concerning vine-water relations on and off heuweltjies and raise questions regarding the origin of the differences. Further, more advanced studies are needed to characterize these differences.

As clearly indicated by the photographs shown, the timing of the vine's phenological stadia differed considerably on and off the heuweltjies. The effects however proved to be totally opposite when the Stellenbosch and Robertson study areas are compared. In Stellenbosch, phenological stadia were delayed, causing budburst on the vines associated with the heuweltjies to occur much later in comparison to the non-heuweltjie vines. This delay was carried through to the ripening stage, where sugar accumulation and berry maturation were also postponed. Again the exact opposite was recorded in the Robertson study area, with the phenological stadia being more advanced on the heuweltjie vines compared to the 'normal' timing of the non-heuweltjie vines.

The differences in soil water content proved to be the main factor distinguishing heuweltjie from non-heuweltjie plots, influencing all of the physiological characteristics. Contrasting findings were found between the two study areas. In the Stellenbosch study area, a higher soil water content was observed on the heuweltjies which led to more vigorous growth of the grapevines and thus denser canopies associated with the heuweltjies. In Robertson however, a lower soil water content was observed on the heuweltjies which resulted in lower vine vigour with less dense canopies. Subsequently, differences were observed in the pruning masses of the experimental vines on and off the heuweltjies, with heuweltjie vines exhibiting significantly stronger vegetative growth in comparison to non-heuweltjie vines in the Stellenbosch study area. This could have negative implications towards yield for heuweltjie-associated vines, decreasing it substantially due to a higher degree of shading with subsequent lower sun exposure. The opposite was observed in Robertson. The more dense canopies led to slower accumulation of sugar in the berries and slower maturation due to excessive vegetative growth and shading of the bunches. This considerably influenced the wine chemical and sensory characteristics, and a clear distinction could be made between wines emanating from heuweltjie and non-heuweltjie vines. Wine chemical and sensory characteristics of heuweltjie wines were most severely affected in the Stellenbosch study area. Chemically, significant differences were found between heuweltjie and non-heuweltjie wine in terms of sugar, acid and alcohol content, with significant variations in sensory attributes such as astringency and alcohol burn sensation. Minor variations were observed in the Robertson study area, but significantly higher fruitiness was found in the wines from the heuweltjie soils in comparison with non-heuweltjie wines.

Significant differences in water content between heuweltjie and non-heuweltjie soils clearly indicate a very distinct variation in the soil-water-plant interaction. The question of irrigation immediately springs to mind and could become a critical factor governing the content of water in the soil, especially in the more arid region of Robertson. Different irrigation frequencies is therefore proposed for heuweltjie and non-heuweltjie vines, thus alleviating the effect of higher and lower vigour with a higher and lower frequency respectively. Different vineyard management practices could also be implemented on the heuweltjies, to nullify the excessively vigorous growth, thus ensuring a more open canopy. Dense canopies can generate a localized climate and management strategies needs to be modified to accompany such variation. The tendency of these vigorous vines to produce long shoots with long internodes and big leaves, as well as a high number of lateral shoots, will severely alter the planning of specific management practices such as shoot repositioning, shoot thinning, tipping, topping and leaf removal.

Due to the extensive variation between heuweltjie and non-heuweltjie vines in terms of berry characteristics and timing of specific growth stadia, specifically ripening, it is recommended that harvesting of the grapes is undertaken separately (as was recently demonstrated on the Stellenbosch study area). This should especially be considered in blocks where heuweltjie density is high, whereas where numbers of heuweltjies are low, this is of lesser significance. Harvesting must be closely observed to ensure that grapes from heuweltjie vines are not mixed with that of non-heuweltjie vines, thereby invalidating the whole objective. Since the wine characteristics varied so significantly between heuweltjie and non-heuweltjie plots, the making of the eventual wine must also be done separately to prevent any loss of desired chemical and sensory attributes, as well as a subsequent decrease in quality through mixing of the two different wines. However, all these recommendations seem very labour intensive and can prove economically unrealistic, as each specific scenario requires new and innovative application of knowledge and expertise.

Summary of possible impacts on agriculture

- Different irrigation scheduling applied to the vines growing on heuweltjies and off the heuweltjies.
- Alternative timing of vineyard management practices, especially canopy management, on and off heuweltjies.
- Different pruning strategies of vines associated with heuweltjies and non-heuweltjie vines.
- Separate harvesting of grapes emanating from heuweltjies due to delayed and hurried ripening in Stellenbosch and Robertson respectively.
- Separate wines to be made from grapes emanating from heuweltjies.

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CHAPTER 5 – SYNTHESIS

This dissertation possesses information that could have a substantial impact on the wine industry, especially in terms of management of heterogeneity in the vineyard. This particular study about the nutrient-enriched termite mounds locally known as 'heuweltjies' (little hills), is the first of its kind in cultivated landscapes and will contribute greatly to the way we think about the legacy of the past activities of *Microhodotermes viator* in agriculture in the Western Cape. Their lasting impacts on the physical and chemical soil properties, owing to nest-building and foraging activities, is transferred to the crops, which initiate differences in vigour, phenology and physiology. Specifically, in the vineyards where this study was carried out, substantial differences were found in the berry characteristics, as well as wine attributes and quality. The latter will undoubtedly will require further investigation, as mechanisms on how to sustain premium wine quality has been a topic of discussion in the local wine industry for decades.

This project stretched over two climatic regions, namely a Mediterranean region and a semi-arid region. We hypothesized that soil physical and chemical properties would vary considerably between heuweltjie and non-heuweltjie soils. We speculated that this might have significant influences on the grapevines associated with the heuweltjies, inducing variation in physiology, phenology, productivity, vine vigour, berry characteristics and ultimately wine quality between heuweltjie and non-heuweltjie vines. Our results supported some of these hypotheses. In terms of soil characteristics, higher pH, exchangeable cation values, total carbon and total nitrogen, and organic carbon were found on the heuweltjie when compared to the adjacent surrounding soils in both study areas. Different soil textures were also detected on and off the heuweltjies, which in turn led to differences in soil water content. This contributed substantially to the observations made on vigour, phenology, physiology, berry characteristics as well as wine characteristics and quality, and was the major factor instigating the differences, opening a whole new can of worms so to speak. Heuweltjies seem to have different effects depending on the climate region and this is mainly due to the fact that heuweltjies tend to retain more water than its surrounding soils in the Mediterranean climate, while heuweltjies have a lower water holding capacity than surrounding soils in the semi-arid climate region. It was this attribute that caused the higher vine vigour in the Stellenbosch study area, which led to significant variation in berry and wine characteristics on and off the heuweltjie. Heuweltjie berries exhibited a higher titratable acid and lower sugar concentration; this was carried over into the wine, which also displayed significantly higher titratable and malic acid concentrations. Heuweltjie wines were also considered to be more 'mild and bland', lacking any exuberance. In Robertson however, the lower water content on the heuweltjie compared to the surrounding soils brought about lower vine vigour, also leading to a difference in some berry and wine characteristics on and off the heuweltjie, but less so than in Stellenbosch. Berries exhibited almost no variation in sugar and titratable acids, but wines were classified to be significantly fruitier off the heuweltjie than on.

Heuweltjies in cultivated landscapes increases pedo-diversity and if managed in the proper manner, it could be profitable. In the past, these differences in vineyards were barely noticed and were included in the vineyard's customary management practices. According to the findings in this dissertation, a different strategy can be proposed which will possibly benefit vineyard block quality, and provide unique and unexplored opportunities to benefit from the legacy of past biodiversity (the activities of the termite). Thus, astute farmers and the wine industry may be able to take advantage by altering their approach to vineyard practices, wine making and wine marketing to increase profitability. Nevertheless, these benefits need to be carefully weighed against economic realities in deciding whether or not it would be viable and sustainable to implement these changes in management.

Possible modifications in agricultural management practices include:

- Implementation of different irrigation scheduling for vines growing on and off heuweltjies
- Alternative timing of vineyard management practices, especially canopy management, on and off heuweltjie.
- Different pruning strategies of vines associated with heuweltjies than non-heuweltjie vines.
- Separate harvesting of grapes emanating from heuweltjies due to delayed and hurried ripening in Stellenbosch and Robertson respectively.
- Separate wines to be made from grapes emanating from heuweltjies and non-heuweltjie vines.

Recommendations for further research are proposed, which include:

- More heuweltjies to experiment on, as the repetitiveness of four heuweltjies per study area is not always defendable.
- Detailed investigation into soil micro-nutrient content occurring on and off heuweltjies, and coupling it with differences in growth patterns, productivity and wine quality.
- Comparison of the cultivated heuweltjies with heuweltjies present in the immediate natural veld, in the same study. For instance, comparing the heuweltjies found in the vineyard at the Robertson study area with the heuweltjies occurring in the foothills bordering the study area less than 500 m away (e.g. Figure 3.8).

This project has granted me the exclusive opportunity to gain perspective on an issue igniting immense curiosity in the agricultural sector. It presented me with the challenge to integrate aspects such as soil, ecology, physiology and wine to better understand and clarify their interactions. Although this is only a drop in the ocean, this dissertation provides fundamental information that will hopefully encourage future research as well as inspire young minds to further their studies in the field of agriculture.

APPENDICES

Appendix 1.1: Terrain and morphological soil characteristics of plot SH1O.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 40.6" / 18° 50' 45.91"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 171 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile between features

Parent – and underlying material: Granite

Soil form and family: Tukulu olivedale

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 200	Dry state; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; few coarse distinct red oxidized iron oxide mottles; structure: apedal medium single grain; consistence: loose, loose; common roots; gradual transition.	Orthic
B	200 - 800	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: clay loam; few coarse distinct red oxidized iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, friable; few clay cutans; many roots; gradual	Neocutanic
C	800 - 1200	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: brownish yellow 10YR6/8; texture: clay loam; few coarse distinct grey reduced iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, friable; few clay cutans; few roots; clear	Unspecified material, with signs of wetness

Appendix 1.2: Terrain and morphological soil characteristics of plot SH1E.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 40.6" / 18° 50' 45.91"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 171 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Granite

Soil form and family: Tukulu olivedale

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 200	Dry state; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: sandy loam; structure: apedal medium single grain; consistence: loose, friable; common roots; gradual transition.	Orthic
B	200 - 700	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: clay loam; common medium faint red and brown iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common sesquioxide cutans; common roots; gradual transition.	Neocutanic
C	700 - 1150	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: strong brown 7.5YR5/6; texture: clay loam; few medium faint grey and white reduced iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; few sesquioxide cutans;	Unspecified material, with signs of wetness

Appendix 1.3: Terrain and morphological soil characteristics of plot SH1C.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 41.51" / 18° 50' 43.99"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 171 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Granite

Soil form and family: Oakleaf buchuberg

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 200	Dry state; dry colour: brown 7.5YR5/4; moist colour: strong brown 7.5YR5/6; texture: sandy clay loam; few medium faint reddish brown oxidized iron oxide mottles; structure: apedal medium single grain; consistence: loose, friable; few sesquioxide cutans; common roots; clear	Orthic
B	200 - 800	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: clay loam; common medium distinct reddish brown oxidized iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common sesquioxide cutans; common roots; clear transition.	Neocutanic
C	800 - 1200	Moist state; dry colour: strong brown 7.5YR5/8; moist colour: brown to dark brown 7.5YR4/4; texture: clay loam; common medium distinct red and brown oxidized iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common sesquioxide cutans; common roots; clear transition.	Neocutanic

Appendix 1.4: Terrain and morphological soil characteristics of plot SH4O.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 40.6" / 18° 50' 45.91"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 168 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile between features

Parent – and underlying material: Granite

Soil form and family: Tukulu olivedale

Surface rockiness: None

Surface stoniness:: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 150	dry colour: strong brown 7.5YR5/8; moist colour: brown to dark brown 7.5YR4/4; texture: sandy loam; few coarse distinct red oxidized iron oxide mottles; structure: apedal medium single grain; consistence: loose, friable; few sesquioxide cutans; common roots; diffuse transition.	Orthic
B	150 - 750	dry colour: strong brown 7.5YR5/6; moist colour: strong brown 7.5YR4/6; texture: clay loam; few coarse distinct red oxidized iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common sesquioxide cutans; common roots;	Neocutanic
C	750 - 1100	dry colour: reddish yellow 7.5YR6/6; moist colour: brownish yellow 10YR6/8; texture: clay loam; few coarse distinct grey reduced iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common clay cutans; few roots; clear	Unspecified material, with signs of wetness

Appendix 1.5: Terrain and morphological soil characteristics of plot SH4E.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 41.51" / 18° 50' 43.99"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 168 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Granite

Soil form and family: Tukulu olivedale

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 1/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 150	Dry state; dry colour: brown to dark brown 10YR4/3; moist colour: very dark brown 10YR2/2; texture: sandy loam; few coarse distinct red oxidized iron oxide mottles; structure: apedal coarse single grain; consistence: loose, loose; common roots; gradual transition.	Orthic
B	150 - 850	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: dark yellowish brown 10YR3/4; texture: clay loam; common coarse distinct red oxidized iron oxide mottles; common coarse distinct black manganese, magnetite mottles; structure: weak medium subangular blocky; consistence: slightly hard, friable; few clay cutans; common roots; gradual transition.	Neocutanic
C	850 - 1100	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: strong brown 7.5YR5/6; texture: clay loam; common medium distinct grey reduced iron oxide mottles; common medium distinct black manganese, magnetite mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; few clay cutans; few roots; clear transition.	Unspecified material, with signs of wetness

Appendix 1.6: Terrain and morphological soil characteristics of plot SH4C.

Map/photo: 3418 BB

Latitude + Longitude: 34° 0' 41.51" / 18° 50' 43.99"

Land Type No: NA

Climate Zone: Mediterranean

Altitude: 168 m

Terrain Unit: Upper Midslope

Slope: 9 %

Slope Shape: Straight

Aspect: North

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Granite

Soil form and family: Oakleaf buchuberg

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 1/2010

Weathering of underlying material: Moderate physical, moderate chemical

Alteration of underlying material: Kaolinised

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 200	Dry state; dry colour: brown to dark brown 10YR4/3; moist colour: very dark brown 10YR2/2; texture: sandy loam; few coarse distinct red oxidized iron oxide mottles; structure: apedal medium angular blocky; consistence: slightly hard, loose; common roots; gradual transition.	Orthic
B	200 - 900	Moist state; dry colour: brown to dark brown 10YR4/3; moist colour: dark yellowish brown 10YR3/4; texture: clay loam; common coarse distinct red oxidized iron oxide mottles; structure: weak medium angular blocky; consistence: hard, slightly firm; few sesquioxide cutans; common roots; gradual transition.	Neocutanic
C	900 - 1100	Moist state; dry colour: brown 7.5YR5/4; moist colour: strong brown 7.5YR5/6; texture: clay loam; many medium distinct red oxidized iron oxide mottles; structure: weak medium angular blocky; consistence: hard, slightly firm; few sesquioxide cutans; few roots; clear transition.	Neocutanic

Appendix 1.7: Terrain and morphological soil characteristics of plot RH2O.

Map/photo: 3319 DD

Latitude + Longitude: 33° 47' 48.7" / 19° 47' 33.8"

Land Type No: NA

Climate Zone: Semi arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile between features

Parent - and underlying material: Alluvium

Soil form and family: Oudtshoorn dysselsdorp

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion : None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 1/2010

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 200	Dry state; dry colour: reddish brown 5YR5/4; moist colour: yellowish red 5YR4/6; texture: medium sand; structure: weak medium single grain; consistence: loose, loose; non-hardened free lime, slight effervescence; common roots; gradual transition.	Orthic
B	200 - 500	Moist state; dry colour: dark yellowish brown 10YR4/6; moist colour: yellowish red 5YR4/6; texture: loamy sand; structure: weak medium subangular blocky; consistence: soft, friable; few roots; clear transition.	Neocutanic
C	500 - 800	Moist state; dry colour: red 2.5YR4/6; moist colour: yellowish red 5YR4/6; texture: medium sand; structure: weak coarse subangular blocky; consistence: soft, friable; discontinuous moderate nodular pan cementation of silica; few mixed-shape coarse stones 75-250mm; few coarse >25mm other fragments; clear transition.	Dorbank

Appendix 1.8: Terrain and morphological soil characteristics of plot RH2E.

Map/photo: 3319DD

Latitude + Longitude: 33° 47' 48.7" / 19° 47' 33.8"

Land Type No: NA

Climate Zone: Semi arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Alluvium

Soil form and family: Augrabies spoegrivier

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 1/2010

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 150	Dry state; dry colour: yellowish brown 10YR5/6; moist colour: yellowish red 5YR4/6; texture: loamy sand; structure: weak medium single grain; consistence: loose, loose; non-hardened free lime, moderate effervescence; common roots; gradual transition.	Orthic
B	150 - 750	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR5/6; texture: sandy loam; structure: weak medium subangular blocky; consistence: slightly hard, firm; non-hardened free lime, strong effervescence; few roots; gradual transition.	Neocarbonate
C	750 - 1200	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: red 2.5YR4/8; texture: silty clay loam; structure: moderate fine subangular blocky; consistence: soft, friable; discontinuous moderate cementation of silica; few mixed-shape coarse stones 75-250mm; very few coarse >25mm other fragments; gradual transition.	Unspecified material, with signs of wetness

Appendix 1.9: Terrain and morphological soil characteristics of plot RH2C.

Map/photo: 3319 DD

Latitude + Longitude: 33° 47' 48.7" / 19° 47' 33.8"

Land Type No: NA

Climate Zone: Semi Arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Alluvium

Soil form and family: Brandvlei kolke

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 1/2010

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 100	Dry state; dry colour: yellowish brown 10YR5/6; moist colour: yellowish red 5YR4/6; texture: medium sand; structure: weak medium single grain; consistence: loose, loose; non-hardened free lime, strong effervescence; many roots; clear transition.	Orthic
B	100 - 700	Moist state; dry colour: brown 7.5YR5/4; moist colour: strong brown 7.5YR4/6; texture: medium sand; structure: weak coarse subangular blocky; consistence: loose, loose; discontinuous strong cementation of carbonates; non-hardened free lime, strong effervescence; very many mixed-shape coarse stones 75-250mm; very many coarse >25mm lime concretions; many roots; gradual transition.	Soft carbonate
C	700 - 1100	Moist state; dry colour: brown 7.5YR5/4; moist colour: strong brown 7.5YR4/6; texture: medium sand; structure: weak coarse subangular blocky; consistence: loose, loose; discontinuous strong cementation of carbonates; non-hardened free lime, strong effervescence; very many mixed-shape coarse stones 75-250mm; very many coarse >25mm lime concretions; few roots; gradual transition.	Soft carbonate

Appendix 1.10: Terrain and morphological soil characteristics of plot RH4O.

Map/photo: 3319 DD

Latitude + Longitude: 33° 47' 52.6" / 19° 47' 41.7"

Land Type No: NA

Climate Zone: Semi arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile between features

Parent - and underlying material: Alluvium

Soil form and family: Valsrivier zuney

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
C	0 - 150	Dry state; dry colour: strong brown 7.5YR4/6; moist colour: yellowish red 5YR4/6; texture: loamy sand; structure: apedal medium single grain; consistence: loose, loose; non-hardened free lime, slight effervescence; many roots; clear transition.	Orthic
B	150 - 400	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR4/6; texture: sandy loam; few medium distinct reddish brown oxidized iron oxide mottles; structure: moderate medium subangular blocky; consistence: slightly hard, slightly firm; common silica cutans; common roots; gradual transition.	Pedocutanic
A	400 - 1000	Moist state; dry colour: yellowish red 5YR5/6; moist colour: yellowish red 5YR4/6; texture: sandy clay loam; structure: moderate coarse subangular blocky; consistence: slightly hard, firm; discontinuous moderate cementation of silica; gradual transition.	Unconsolidated material, without signs of wetness

Appendix 1.11: Terrain and morphological soil characteristics of plot RH4E.

Map/photo: 3319 DD

Latitude + Longitude: 33° 47' 52.6" / 19° 47' 41.7"

Land Type No: NA

Climate Zone: Semi arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent – and underlying material: Alluvium

Soil form and family: Augrabies hefnaar

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Unknown

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 150	Dry state; dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR5/6; texture: medium sand; structure: apedal medium single grain; consistence: loose, loose; non-hardened free lime, moderate effervescence; many roots; gradual transition.	Orthic
B	150 - 600	Moist state; dry colour: strong brown 7.5YR4/6; moist colour: yellowish red 5YR4/6; texture: loamy coarse sand; structure: weak medium subangular blocky; consistence: soft, friable; discontinuous strong cementation of carbonates; non-hardened free lime, strong effervescence; common mixed-shape stones 25-75mm; many roots; gradual transition.	Neocarbonate
C	600 - 1100	Moist state; dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR4/6; texture: loamy medium sand; structure: weak medium subangular blocky; consistence: soft, friable; non-hardened free lime, strong effervescence; few roots; gradual transition.	Neocarbonate

Appendix 1.12: Terrain and morphological soil characteristics of plot RH4C.

Map/photo: 3319 DD

Latitude + Longitude: 33° 47' 52.6" / 19° 47' 41.7"

Land Type No: NA

Climate Zone: Semi arid

Altitude: 207 m

Terrain Unit: Terrace

Slope: 1 %

Slope Shape: Straight

Aspect: South-west

Microrelief: Anthill mounds, m, % coverage, profile within features

Parent - and underlying material: Alluvium

Soil form and family: Augrabies hefnaar

Surface rockiness: None

Surface stoniness: None

Occurrence of flooding: None

Wind erosion: None

Water Erosion: None

Vegetation / Land use: Vineyards

Water table: None

Described by: SJ Bekker

Date described: 6/2010

Weathering of underlying material: Weak physical, weak chemical

Alteration of underlying material: Calcified

Horizon	Depth (mm)	Description	Diagnostic horizon
A	0 - 150	Dry state; dry colour: strong brown 7.5YR5/6; moist colour: yellowish red 5YR4/6; texture: medium sand; structure: apedal medium single grain; consistence: loose, loose; non-hardened free lime, strong effervescence; many roots; gradual transition.	Orthic
B	150 - 750	Moist state; dry colour: strong brown 7.5YR4/6; moist colour: yellowish red 5YR4/6; texture: loamy coarse sand; structure: weak coarse subangular blocky; consistence: soft, friable; discontinuous strong cementation of carbonates; non-hardened free lime, strong effervescence; many mixed-shape stones 25-75mm; many roots; gradual transition.	Neocarbonate
C	750 - 1300	Moist state; dry colour: reddish yellow 7.5YR6/6; moist colour: yellowish red 5YR4/6; texture: sandy loam; structure: weak medium subangular blocky; consistence: soft, friable; discontinuous strong cementation of carbonates; non-hardened free lime, strong effervescence; many mixed-shape stones 25-75mm; common roots; gradual transition	Neocarbonate

Appendix 1.13: Bulk density values of the different sites in the Stellenbosch study area.

		Bulk density (g.cm^{-3})	
Heuweltjie	**Depth (cm)**	**Heuweltjie**	**Non-heuweltjie**
1	0-20	1.34	1.65
	20-50	1.66	1.60
	50-80	1.59	1.52
	80-100	1.60	1.39
2	0-20	1.34	1.36
	20-50	1.45	1.56
	50-80	1.93	1.85
	80-100	1.57	1.36
3	0-20	1.35	1.35
	20-50	1.55	1.48
	50-80	1.48	1.55
	80-100	1.73	1.78
4	0-20	1.34	1.20
	20-50	1.63	1.80
	50-80	1.59	1.66
	80-100	1.68	1.52

Appendix 1.14: Volumetric water contents (mm) of the soils from heuweltjie and non-heuweltjie plots in the Stellenbosch study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (mm) that occurred from that plots.

Heuweltjie 1								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	41.5	27.6	14.0	16.9	26.2	19.9	48.8
	30-50	33.8	29.8	17.5	14.9	19.9	21.1	42.2
	50-80	38.3	32.1	21.8	15.9	22.0	24.1	42.3
	80-100	49.6	44.8	28.6	24.8	27.5	28.6	49.2
	Total	**163.3**	**134.3**	**81.8**	**72.6**	**95.6**	**93.8**	**182.5**
	Difference	x	28.9	52.5	9.2	-23.0	1.8	-88.7
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	29.2	60.4	23.5	38.8	12.2	53.2
	ET/day	x	1.3	2.2	0.9	1.4	0.3	1.6
Non-heuweltjie 1								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	34.9	23.7	19.8	16.8	18.6	15.0	50.8
	30-50	33.3	27.3	18.9	11.7	16.8	17.8	41.8
	50-80	37.9	28.4	17.8	12.9	20.0	18.1	45.1
	80-100	40.9	38.7	20.7	16.3	20.3	22.8	43.6
	Total	**147.1**	**118.1**	**77.2**	**57.7**	**75.7**	**73.6**	**181.4**
	Difference	x	29.0	40.9	19.5	-17.9	2.0	-107.7
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	29.3	48.7	33.7	43.9	12.5	34.2
	ET/day	x	1.3	1.8	1.3	1.6	0.4	1.0

Appendix 1.14: Volumetric water contents (θv) of the soils from heuweltjie and non-heuweltjie plots in the Stellenbosch study area over the course of seven months (November 2009 to May 2010), as well as the evapotranspiration (ET) that occurred from that plots (continued).

Heuweltjie 2								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	45.5	23.8	12.0	14.8	18.6	20.1	44.9
	30-50	41.2	28.2	17.1	14.2	16.3	18.6	38.6
	50-80	38.1	30.7	22.0	14.6	17.5	19.2	40.7
	80-100	43.6	38.9	27.6	18.3	20.5	19.6	40.7
	Total	**168.3**	**121.6**	**78.7**	**61.9**	**72.9**	**77.5**	**164.8**
	Difference	x	46.6	42.9	16.8	-11.0	-4.6	-87.4
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	46.9	50.8	31.1	50.9	5.8	54.6
	ET/day	x	2.1	1.9	1.2	1.9	0.2	1.6
Non-heuweltjie 2								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	41.9	26.9	13.0	9.9	23.6	19.5	39.9
	30-50	39.5	28.3	15.8	9.0	19.7	16.5	35.1
	50-80	40.7	29.2	16.4	8.2	17.1	13.7	36.6
	80-100	47.2	38.8	24.1	16.0	23.5	16.2	43.6
	Total	**169.3**	**123.2**	**69.4**	**43.1**	**83.9**	**65.8**	**155.2**
	Difference	x	46.1	53.8	26.2	-40.8	18.1	-89.4
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	46.3	61.7	40.5	21.0	28.5	52.6
	ET/day	x	2.1	2.3	1.6	0.8	0.8	1.5

Appendix 1.14: Volumetric water contents (θv) of the soils from heuweltjie and non-heuweltjie plots in the Stellenbosch study area over the course of seven months (November 2009 to May 2010), as well as the evapotranspiration (ET) that occurred from that plots (continued).

Heuweltjie 3								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	39.1	22.7	15.4	6.1	20.8	19.7	42.7
	30-50	39.5	27.7	17.5	6.9	17.1	19.4	34.5
	50-80	34.2	31.4	12.3	7.8	13.5	15.7	34.8
	80-100	44.2	39.1	10.2	10.2	20.0	18.5	34.8
	Total	**156.9**	**120.8**	**55.4**	**30.9**	**71.4**	**73.3**	**146.8**
	Difference	x	36.1	65.4	24.5	-40.5	-1.9	-73.5
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	36.4	73.3	38.7	21.3	8.5	68.5
	ET/day	x	1.7	2.7	1.5	0.8	0.2	2.0
Non-heuweltjie 3								
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	29.7	14.9	7.3	9.8	15.6	20.1	31.0
	30-50	33.6	19.3	4.0	10.0	15.4	15.5	28.5
	50-80	40.7	31.3	10.5	16.7	19.0	21.3	40.2
	80-100	55.0	35.5	17.9	16.5	18.3	26.5	37.0
	Total	**159.0**	**101.0**	**39.8**	**53.1**	**68.3**	**83.4**	**136.7**
	Difference	x	57.9	61.3	-13.3	-15.2	-15.1	-53.3
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	58.2	69.1	1.0	46.6	-4.7	88.7
	ET/day	x	2.6	2.6	0.0	1.7	-0.1	2.6

Appendix 1.14: Volumetric water contents (θv) of the soils from heuweltjie and non-heuweltjie plots in the Stellenbosch study area over the course of seven months (November 2009 to May 2010), as well as the evapotranspiration (ET) that occurred from that plots (continued).

	Heuweltjie 4							
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	49.4	25.8	24.4	17.0	23.6	16.7	50.3
	30-50	49.5	26.0	22.4	17.9	22.6	17.6	51.3
	50-80	51.8	33.6	30.1	22.6	24.6	20.4	53.2
	80-100	54.2	44.4	30.2	24.2	26.8	28.6	50.7
	Total	**204.9**	**129.9**	**107.1**	**81.6**	**97.7**	**83.3**	**205.5**
	Difference	x	75.1	22.7	25.5	-16.1	14.4	-122.2
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	75.3	30.6	39.8	45.8	24.8	19.7
	ET/day	x	3.4	1.1	1.5	1.7	0.7	0.6
	Non-heuweltjie 4							
	Date	**2009/11/16**	**2009/12/09**	**2010/01/06**	**2010/02/02**	**2010/03/02**	**2010/04/07**	**2010/05/12**
Depth (cm)	0-30	37.0	24.0	24.0	10.3	22.4	10.8	48.0
	30-50	33.3	24.7	19.4	9.1	23.4	14.0	39.0
	50-80	32.2	31.0	25.2	17.9	27.1	23.2	44.9
	80-100	37.9	42.1	37.6	31.9	40.3	29.4	55.0
	Total	**140.4**	**121.8**	**106.3**	**69.1**	**113.3**	**77.4**	**186.9**
	Difference	x	18.5	15.5	37.1	-44.1	35.8	-109.4
	Rainfall	x	0.3	7.9	0.5	37.1	10.4	142.0
	Irrigation	x	0	0	13.8	24.8	0	0
	ET	x	18.8	23.4	51.4	17.7	46.2	32.5
	ET/day	x	0.9	0.9	2.0	0.7	1.3	1.0

Appendix 1.15: pH values in water of the different soil samples at all four sites in the Stellenbosch study area.

pH in water								
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Mid N**	**Crest**	**Mid S**	**Edge S**	**Off S**
1	0-20	7.35	7.45	7.49	7.36	7.39	7.63	7.66
	20-40	7.72	7.56	7.67	7.61	7.58	7.66	7.86
	40-60	7.65	7.56	7.69	7.54	7.58	7.64	7.88
	60-80	7.64	7.33	7.54	7.3	7.32	7.15	7.78
	80-100	6.78	7.2	7.23	7.23	6.73	6.39	5.81
2	0-20	7.31	7.4	7.12	7.43	7.34	7.46	7.48
	20-40	6.69	7.43	7.21	7.58	7.31	7.67	7.71
	40-60	6.04	7.02	6.74	7.48	7.22	6.53	7.81
	60-80	5.88	6.2	6.48	7.21	6.35	6.1	7.08
	80-100	5.51	5.97	6.48	6.85	6.17	5.66	6.22
3	0-20	6.66	6.64	6.92	6.27	6.46	6.43	5.76
	20-40	6.25	7.56	6.19	6.38	6.49	5.88	6.44
	40-60	5.74	6.59	5.83	6.03	6.21	5.98	5.92
	60-80	5.58	6.44	5.74	6.01	6.17	5.8	5.73
	80-100	5.45	5.54	5.9	6	5.97	5.94	5.89
4	0-20	6.88	6.72	6.79	6.92	6.34	6.67	6.97
	20-40	6.52	6.8	6.35	7.17	6.41	6.71	6.61
	40-60	6.23	6.96	6.12	7.23	6.45	6.41	6.4
	60-80	6.11	6.56	6.44	7.14	6.5	6.22	6.39
	80-100	5.97	6.09	6.48	7.3	6.36	6.02	6.4
Average		6.5	6.85	6.72	7	6.72	6.6	6.79

Appendix 1.16: pH values in KCl of the different soil samples at all four sites in the Stellenbosch study area.

pH KCl								
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Mid N**	**Crest**	**Mid S**	**Edge S**	**Off S**
1	0-20	6.14	6.09	6.23	6.03	6.07	6.44	6.43
	20-40	6.71	6.36	6.45	6.46	6.34	6.72	6.88
	40-60	6.76	6.46	6.52	6.41	6.46	6.66	6.89
	60-80	6.56	6.38	6.44	6.13	6.26	6.22	6.76
	80-100	5.96	6.37	6.1	6.13	5.96	5.64	5.04
2	0-20	6.05	6.18	5.87	6.33	6.14	6.33	6.33
	20-40	5.46	6.1	5.97	6.44	5.98	6.74	6.54
	40-60	4.96	5.79	5.68	6.26	5.97	5.65	6.73
	60-80	4.96	5.18	5.39	5.91	5.34	5.18	6.14
	80-100	4.67	5.07	5.44	5.71	5.28	4.94	5.42
3	0-20	5.92	5.79	5.75	5.32	5.33	5.29	5.15
	20-40	5.46	6.55	5.23	5.15	5.27	4.91	5.34
	40-60	5.02	5.71	5.01	5.04	5.12	4.94	5.02
	60-80	4.89	5.77	5.01	5.12	5.13	4.94	4.95
	80-100	4.58	4.75	5.16	5.13	5.25	5.14	5.05
4	0-20	5.79	5.31	4.82	5.73	4.94	5.43	5.67
	20-40	5.41	5.16	4.86	5.82	4.91	5.37	5.5
	40-60	5.21	5.47	4.96	5.78	5.07	5.09	5.36
	60-80	4.84	5.32	5.15	5.71	5.06	5.11	5.21
	80-100	5.39	5.86	5.03	5.65	4.95	5.12	5.46
Average		5.54	5.78	5.55	5.81	5.54	5.59	5.79

Appendix 1.17: EC values as a 1:5 extract of the different soil samples at all four sites in the Stellenbosch study area.

EC 1:5 extract								
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Mid N**	**Crest**	**Mid S**	**Edge S**	**Off S**
1	0-20	5.92	4.54	4.61	4.7	4.57	5.45	4.8
	20-40	5.66	3.9	4.35	4.71	4.11	5.68	6.52
	40-60	6.17	4.91	4.76	5.28	4.37	5.87	6.36
	60-80	5.53	5.8	5.57	4.94	5.2	6.87	6.26
	80-100	9.56	5.93	5.84	5.45	6.24	8.06	9.33
2	0-20	5.17	5.36	5.14	5.87	5.7	6.07	5.54
	20-40	5.24	4.01	4.24	5.09	4.15	9.48	4.55
	40-60	6.63	4.85	5.41	4.82	5.63	13.76	7.39
	60-80	8.58	7.61	6.18	4.71	6.5	11.82	7.5
	80-100	9.06	9.07	6.58	5.98	8.11	16.08	7.92
3	0-20	10.27	13.72	8.3	9.23	9.47	9.25	24.1
	20-40	15.51	10.47	9.22	7.51	7.42	9.93	8.06
	40-60	11.17	11.92	7.99	8.06	6.44	7.62	6.65
	60-80	9.2	11.88	7.97	6.99	7.15	8.14	7.99
	80-100	9.28	10.89	7.88	6.92	7.12	6.71	6.34
4	0-20	4.98	5.66	4.54	6.75	4.73	5.94	5.08
	20-40	6.95	4.26	4.13	4.74	3.87	4.34	6.7
	40-60	4.97	4.21	4.88	4.11	4.99	5.62	5.48
	60-80	7.72	5.81	5.56	4.08	4.78	7.61	5.07
	80-100	8.22	5.67	5.09	3.81	4.44	7.74	6.01
Average		7.79	7.02	5.91	5.69	5.75	8.1	7.38

Appendix 1.18: EC values as a saturated paste extract of the different soil samples at all four sites in the Stellenbosch study area.

EC Saturated paste			
Site	**Depth**	**Resistance (Ω)**	**EC value (mS/m)**
Crest	0-20	1031	27.16
	40-60	1301	21.52
	80-100	1488	18.82
Edge	0-20	1025	27.33
	40-60	1996	14.03
	80-100	1950	14.39
Off	0-20	1410	19.85
	40-60	2070	13.52
	80-100	1968	14.22

Appendix 1.19: Exchangeable cation contents of the different soil samples at three sites in the Stellenbosch study area.

Ca (cmol/kg)						
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Crest**	**Edge S**	**Off S**
1	0-20	5.369	4.84	5.898	5.893	5.998
	40-60	4.381	4.212	5.309	5.105	7.051
	80-100	3.144	3.034	3.373	2.645	2.4
2	0-20	4.755	4.94	6.961	6.252	5.399
	40-60	2.759	3.643	5.16	4.486	6.707
	80-100	1.871	2.28	3.528	2.4	2.585
4	0-20	4.247	4.716	6.148	3.967	3.787
	40-60	2.345	3.578	5.145	3.164	4.676
	80-100	2.121	2.405	4.94	2.021	2.156
Mg (cmol/kg)						
1	0-20	0.947	0.922	1.004	0.634	0.609
	40-60	0.881	1.193	1.251	0.724	0.617
	80-100	0.881	1.128	1.416	0.626	0.477
2	0-20	0.584	0.691	0.897	0.56	0.469
	40-60	0.551	0.7	1.152	0.617	0.551
	80-100	0.675	0.733	1.086	0.601	0.395
4	0-20	0.551	0.601	1.3	0.922	1.037
	40-60	0.486	0.519	1.638	1.119	1.342
	80-100	0.658	0.675	1.663	1.391	1.523

Appendix 1.19: Exchangeable cation contents of the different soil samples at three sites in the Stellenbosch study area (continued).

Na (cmol/kg)						
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Crest**	**Edge S**	**Off S**
1	0-20	0.204	0.217	0.148	0.126	0.139
	40-60	0.144	0.183	0.17	0.152	0.126
	80-100	0.344	0.374	0.287	0.291	0.287
2	0-20	0.339	0.326	0.339	0.352	0.326
	40-60	0.3	0.352	0.374	0.357	0.326
	80-100	0.27	0.318	0.378	0.326	0.296
4	0-20	0.274	0.318	0.265	0.274	0.287
	40-60	0.304	0.287	0.309	0.3	0.248
	80-100	0.283	0.313	0.331	0.265	0.287
K (cmol/kg)						
1	0-20	0.928	0.811	0.995	0.76	0.931
	40-60	0.309	0.228	0.256	0.169	0.276
	80-100	0.379	0.184	0.156	0.13	0.159
2	0-20	0.458	0.54	0.087	0.604	0.596
	40-60	0.164	0.182	0.1	0.217	0.182
	80-100	0.151	0.179	0.169	0.297	0.164
4	0-20	0.486	0.496	0.199	0.752	0.793
	40-60	0.153	0.164	0.22	0.238	0.233
	80-100	0.133	0.1	0.223	0.205	0.284

Appendix 1.20: Extractable phosphorous contents of the different soil samples at three sites in the Stellenbosch study area.

P mg/kg						
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Crest**	**Edge S**	**Off S**
1	0-20	22.7	15.5	23.8	14.8	17.8
	40-60	8.1	9.7	9.7	8.6	18.2
	80-100	9.5	7.1	7.3	5.7	4.1
2	0-20	25.7	15.1	15.9	19.0	14.3
	40-60	38.7	7.9	6.8	25.4	18.7
	80-100	4.4	4.8	5.7	4.8	4.1
4	0-20	12.8	19.5	11.7	9.7	19.5
	40-60	5.9	8.7	5.2	6.0	9.8
	80-100	47.6	4.3	6.8	4.3	4.8

Appendix 1.21: Total carbon and nitrogen contents of the different soil samples at three sites in the Stellenbosch study area.

Total C %						
Heuweltjie	**Depth**	**Off N**	**Edge N**	**Crest**	**Edge S**	**Off S**
1	0-20	1.63	1.39	1.43	1.23	1.31
	40-60	0.79	1.21	0.99	0.86	1.15
	80-100	0.76	0.59	0.72	0.44	0.46
2	0-20	1.58	1.27	1.05	1.17	1.37
	40-60	1.14	1.14	1.18	0.82	0.93
	80-100	0.98	0.53	0.58	0.65	0.6
4	0-20	1.15	1.31	1.68	1.42	1.43
	40-60	0.58	0.78	1.26	1.25	0.81
	80-100	0.45	0.44	1.24	0.73	0.87
Total N %						
1	0-20	0.11	0.11	0.11	0.21	0.07
	40-60	0.05	0.05	0.06	0.07	0.07
	80-100	0.06	0.03	0.05	0.09	0.03
2	0-20	0.08	0.06	0.09	0.12	0.08
	40-60	0.1	0.05	0.07	0.06	0.07
	80-100	0.07	0.04	0.07	0.04	0.05
4	0-20	0.08	0.09	0.15	0.09	0.1
	40-60	0.03	0.05	0.1	0.09	0.06
	80-100	0.02	0	0.09	0.04	0.04

Appendix 1.22: Organic carbon content of the different soil samples at one site in the Stellenbosch study area.

Organic C %				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
4	0-20	1.386	1.542	1.272
	40-60	1.229	1.213	0.832
	80-100	0.647	1.172	0.795

Appendix 2.1: Bulk density values of the different sites in the Robertson study area

		Bulk density ($g.cm^{-3}$)	
Heuweltjie	**Depth (cm)**	**Heuweltjie**	**Non-heuweltjie**
1	0-20	1.458	1.554
	20-50	1.649	1.672
	50-80	1.366	1.522
	80-100	1.768	1.746
2	0-20	1.489	1.385
	20-50	1.450	1.391
	50-80	1.248	1.394
	80-100	1.809	1.413
3	0-20	1.305	1.281
	20-50	1.575	1.467
	50-80	1.520	1.559
	80-100	1.430	1.531
4	0-20	1.177	1.403
	20-50	1.228	1.577
	50-80	1.205	1.404
	80-100	1.334	1.572

Appendix 2.2: Volumetric water contents (mm) of the soils from heuweltjie and non-heuweltjie plots in the Robertson study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (mm) that occurred from that plots.

Heuweltjie 1								
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	11.7	18.2	16.4	16.6	18.0	13.6	19.4
	30-50	10.1	13.5	13.6	12.2	14.6	12.5	15.1
	50-80	9.4	10.9	11.2	7.3	14.2	11.8	14.3
	80-100	13.3	11.1	11.2	7.5	11.6	13.5	14.9
	Total	**44.5**	**53.7**	**52.4**	**43.7**	**58.4**	**51.4**	**63.8**
	Difference	x	-9.283	1.377	8.645	-14.658	6.972	-12.407
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	106.7	124.3	96.7	100	60
	ET	x	96.117	117.121	137.545	125.842	118.772	51.493
	ET/day	x	4.806	4.338	5.094	4.840	3.393	2.146
Non-heuweltjie 1								
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	10.6	13.0	13.0	10.8	17.5	12.4	12.5
	30-50	13.8	10.6	12.4	8.8	15.8	13.5	10.3
	50-80	14.0	9.0	13.8	8.3	14.6	15.9	12.6
	80-100	15.4	10.2	14.3	10.2	16.1	18.1	15.6
	Total	**53.7**	**42.8**	**53.6**	**38.1**	**64.1**	**59.8**	**51.0**
	Difference	x	10.929	-10.801	15.447	-25.945	4.240	8.801
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	106.7	124.3	96.7	100	60
	ET	x	116.329	104.942	144.347	114.555	116.040	72.701
	ET/day	x	5.816	3.887	5.346	4.406	3.315	3.029

Appendix 2.2: Volumetric water contents (mm) of the soils from heuweltjie and non-heuweltjie plots in the Robertson study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (mm) that occurred from that plots (continued).

Heuweltjie 2								
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	11.1	14.7	12.7	15.9	14.1	12.0	14.6
	30-50	11.0	14.4	12.9	10.4	13.2	12.0	15.6
	50-80	10.8	11.9	11.9	10.2	12.9	13.4	15.7
	80-100	14.5	13.1	12.0	8.9	13.3	15.7	16.9
	Total	**47.4**	**53.9**	**49.5**	**45.4**	**53.5**	**53.2**	**62.8**
	Difference	x	-6.522	4.420	4.129	-8.138	0.337	-9.645
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	106.7	124.3	96.7	100	60
	ET	x	98.878	120.163	133.029	132.362	112.137	54.255
	ET/day	x	4.299	4.292	4.587	4.902	3.115	2.170
Non-heuweltjie 2								
Depth (cm)	0-30	17.0	21.4	21.4	21.5	22.5	18.3	18.8
	30-50	12.6	10.5	17.7	12.8	15.2	15.3	15.4
	50-80	13.2	13.3	18.6	12.5	14.1	15.5	13.1
	80-100	19.8	20.9	24.2	16.0	16.5	20.2	15.6
	Total	**62.6**	**66.1**	**82.0**	**62.8**	**68.2**	**69.3**	**62.9**
	Difference	x	-3.550	-15.910	19.244	-5.434	-1.062	6.419
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	106.7	124.3	96.7	100	60
	ET	x	101.850	99.833	148.144	135.066	110.738	70.319
	ET/day	x	4.428	3.565	5.108	5.002	3.076	2.813

Appendix 2.2: Volumetric water contents (mm) of the soils from heuweltjie and non-heuweltjie plots in the Robertson study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (mm) that occurred from that plots (continued).

Heuweltjie 3								
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	13.1	19.8	15.4	16.0	17.9	9.0	12.7
	30-50	9.1	13.1	10.9	10.5	11.8	9.2	11.7
	50-80	11.1	11.3	11.0	8.9	10.1	9.8	11.4
	80-100	14.4	11.3	12.4	8.0	11.7	11.0	13.3
	Total	**47.7**	**55.5**	**49.7**	**43.3**	**51.6**	**39.0**	**49.1**
	Difference	x	-7.765	5.810	6.376	-8.243	12.555	-10.124
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	108.4	123.5	103.4	105	60
	ET	x	97.635	123.210	134.476	138.957	129.355	53.776
	ET/day	x	4.245	4.400	4.637	5.147	3.593	2.151
Non-heuweltjie 3								
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	14.6	13.5	7.6	5.2	15.9	12.4	13.7
	30-50	14.3	13.0	8.9	14.1	14.1	12.0	13.7
	50-80	15.7	12.5	10.8	9.2	13.5	13.4	13.1
	80-100	19.7	17.7	13.3	11.7	15.1	16.3	14.8
	Total	**64.3**	**56.8**	**40.6**	**40.2**	**58.6**	**54.1**	**55.3**
	Difference	x	7.533	16.155	0.439	-18.382	4.464	-1.231
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	108.4	123.5	103.4	105	60
	ET	x	112.933	133.555	128.539	128.818	121.264	62.669
	ET/day	x	4.910	4.770	4.432	4.771	3.368	2.507

Appendix 2.2: Volumetric water contents (mm) of the soils from heuweltjie and non-heuweltjie plots in the Robertson study area over the course of seven months (November 2009 to May 210), as well as the evapotranspiration (mm) that occurred from that plots (continued).

	Heuweltjie 4							
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	19.1	22.0	19.4	19.9	21.3	22.5	22.2
	30-50	15.6	14.9	13.9	14.1	15.8	18.5	16.9
	50-80	13.9	11.4	11.6	10.5	11.8	15.2	14.4
	80-100	15.6	13.8	12.4	10.4	10.2	15.3	14.1
	Total	**64.2**	**62.1**	**57.3**	**54.9**	**59.0**	**71.6**	**67.5**
	Difference	x	2.172	4.753	2.421	-4.099	-12.571	4.041
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	108.4	113.5	103.4	100	60
	ET	x	107.572	122.153	120.521	143.101	99.229	67.941
	ET/day	x	4.677	4.363	4.156	5.300	2.756	2.718
	Non-heuweltjie 4							
	Date	**2009/11/19**	**2009/12/10**	**2010/01/07**	**2010/02/04**	**2010/03/03**	**2010/04/08**	**2010/05/03**
Depth (cm)	0-30	17.3	21.1	21.5	25.1	22.2	27.8	21.6
	30-50	17.1	26.1	22.6	25.8	22.0	25.7	20.4
	50-80	22.1	23.1	23.8	25.9	25.7	28.2	23.9
	80-100	20.1	20.7	22.6	23.7	23.9	27.9	23.0
	Total	**76.5**	**91.0**	**90.4**	**100.6**	**93.8**	**109.6**	**88.9**
	Difference	x	-14.455	0.584	-10.197	6.810	-15.805	20.683
	Rainfall	x	5.4	9	4.6	43.8	11.8	3.9
	Irrigation	x	100.0	108.4	113.5	103.4	100	60
	ET	x	90.945	117.984	107.903	154.010	95.995	84.583
	ET/day	x	3.954	4.214	3.721	5.704	2.667	3.383

Appendix 2.3: pH values in water of the different soil samples at all four sites in the Robertson study area.

pH in water				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
1	0-20	8.1	8.2	8.07
	20-40	8.63	8.5	8.48
	40-60	8.88	9	8.34
	60-80	8.84	9.08	8.5
	80-100	8.92	9.22	8.13
2	0-20	8.43	8.04	8.26
	20-40	8.86	7.98	8.23
	40-60	9.01	8.24	8.27
	60-80	9.11	8.56	7.88
	80-100	9.18	8.43	7.1
3	0-20	8.56	8.62	8.11
	20-40	8.27	8.35	8.47
	40-60	8.07	9.01	7.41
	60-80	8.69	9.18	7.65
	80-100	8.79	8.84	6.68
4	0-20	8.78	8.8	7.94
	20-40	8.29	8.92	7.64
	40-60	8.7	8.88	7.36
	60-80	8.84	8.66	6.82
	80-100	8.81	8.73	5.42
Average		8.688	8.662	7.738

Appendix 2.4: pH values in KCl of the different soil samples at all four sites in the Robertson study area.

pH in KCl				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
1	0-20	8.03	8.01	8.02
	20-40	8.36	8.24	8.17
	40-60	8.44	8.4	8.12
	60-80	8.63	8.58	7.57
	80-100	8.65	8.74	7.53
2	0-20	8.3	7.94	8.18
	20-40	8.4	7.76	8.15
	40-60	8.38	8.05	7.99
	60-80	8.28	8.28	7.35
	80-100	8.24	8.28	5.95
3	0-20	8	7.96	7.94
	20-40	7.95	7.95	7.91
	40-60	7.74	8.17	7.38
	60-80	7.81	8.25	7.5
	80-100	8.06	8.21	5.81
4	0-20	7.95	7.98	7.68
	20-40	7.97	7.98	7.02
	40-60	8.12	7.94	6.21
	60-80	8.18	7.92	5.43
	80-100	8.25	7.98	4
Average		8.187	8.131	7.1955

Appendix 2.5: EC values as a 1:5 extract of the different soil samples at all four sites in the Robertson study area.

EC 1:5 extract				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
1	0-20	181.2	203	168.3
	20-40	21.9	25.5	21.7
	40-60	12.03	10.74	26
	60-80	15.13	13.31	10.03
	80-100	15.66	12.9	23.3
2	0-20	51.3	115.7	189.1
	20-40	18.37	203	97.9
	40-60	12.63	79.8	34.5
	60-80	13.34	34.9	44.3
	80-100	27.5	60.1	49.4
3	0-20	26.5	17.57	136
	20-40	40.5	44.5	14.1
	40-60	82.8	13.07	109.2
	60-80	27.4	12.94	59.2
	80-100	35.6	26.3	39.6
4	0-20	13.52	15.41	41.4
	20-40	58.4	14.77	21.1
	40-60	19.3	16.08	15.2
	60-80	16.25	22.4	12.04
	80-100	20.5	18.73	25
5	0-20	161.1	179.8	161.8
	20-40	61.8	15.57	170.2
	40-60	35.2	58.8	36.9
	60-80	41.9	40.7	64.9
	80-100	50.3	60.5	53.7
Average		**42.4052**	**52.6436**	**64.9948**

Appendix 2.6: EC values as a saturated paste extract of the different soil samples at all four sites in the Robertson study area.

EC Saturated paste extract			
	Depth	**Resistance (Ω)**	**EC value (mS/m)**
Crest	0-20	316.7	325
	20-40	314	324
	40-60	339.6	309
	60-80	345.3	306
	80-100	348.3	324
Edge	0-20	339.5	327
	20-40	687.2	187.3
	40-60	1020	103
	60-80	1155	95.5
	80-100	347.1	285
Off	0-20	207.8	573
	20-40	396.2	421
	40-60	394.1	426
	60-80	189.6	633
	80-100	163.4	679

Appendix 2.7: Exchangeable cation contents of the different soil samples at three sites in the Robertson study area.

Ca (cmol/kg)				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
2	0-20	11.826	16.018	20.16
	40-60	8.533	15.22	5.739
	80-100	4.491	11.976	3.543
3	0-20	8.982	10.479	13.972
	40-60	12.874	10.479	10.23
	80-100	5.539	7.385	2.745
4	0-20	11.527	12.974	9.481
	40-60	15.469	13.972	6.836
	80-100	13.822	11.477	2.745
Mg (cmol/kg)				
2	0-20	0.905	0.741	1.564
	40-60	1.893	1.481	0.658
	80-100	2.798	1.07	1.975
3	0-20	0.988	1.235	0.494
	40-60	1.646	1.811	0.658
	80-100	3.457	1.811	0.576
4	0-20	1.893	1.728	0.823
	40-60	1.481	1.975	1.07
	80-100	3.621	1.811	2.963

Appendix 2.7: Exchangeable cation contents of the different soil samples at three sites in the Robertson study area (continued).

Na (cmol/kg)				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
2	0-20	0.478	0.387	0.748
	40-60	0.426	0.522	0.783
	80-100	1.131	0.474	2.318
3	0-20	0.687	0.626	0.635
	40-60	0.679	0.579	0.413
	80-100	1.409	0.718	0.5
4	0-20	0.57	0.822	0.348
	40-60	0.422	0.839	0.609
	80-100	0.418	0.613	1.479
K (cmol/kg)				
2	0-20	3.772	2.798	4.371
	40-60	4.555	2.079	4.642
	80-100	4.527	3.133	3.563
3	0-20	2.307	2.263	2.358
	40-60	1.353	2.286	0.977
	80-100	1.673	2.391	3.077
4	0-20	3.092	3.235	0.542
	40-60	2.11	2.171	0.379
	80-100	0.381	2.097	0.581

Appendix 2.8: Extractable phosphorous contents of the different soil samples at three sites in the Robertson study area.

P mg/kg				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
2	0-20	143	93	122
	40-60	30	13	9
	80-100	14	13	3
3	0-20	78	133	89
	40-60	22	38	37
	80-100	20	27	7
4	0-20	208	68	119
	40-60	67	12	8
	80-100	76	26	2

Appendix 2.9: Total carbon and nitrogen contents of the different soil samples at three sites in the Robertson study area.

Total C %				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
2	0-20	1.4	1.76	1.1
	40-60	0.59	0.2	0.48
	80-100	0.2	0.95	0.42
3	0-20	0.68	0.83	0.76
	40-60	0.48	0.53	0.4
	80-100	0.16	0.2	0.32
4	0-20	1.2	2.22	1.44
	40-60	1.9	1.5	0.76
	80-100	1.9	0.76	0.38
Total N %				
2	0-20	0.11	0.11	0.09
	40-60	0.09	0.04	0.04
	80-100	0.04	0.04	0.06
3	0-20	BD*	0.02	0.07
	40-60	0.04	BD*	BD*
	80-100	0.04	0.04	BD*
4	0-20	0.09	0.04	0.14
	40-60	0.05	0.12	0.01
	80-100	0.03	0.12	0.02

***** BD – Below detection

Appendix 2.10: Organic carbon content of the different soil samples at one site in the Robertson study area.

Organic C %				
Heuweltjie	**Depth**	**Edge**	**Crest**	**Off**
4	0-20	0.86	0.88	1.09
	40-60	1.47	0.35	0.68
	80-100	1.48	0.23	0.39

Appendix 3.1: Stomatal conductance readings taken over the five experimental months in the Stellenbosch study area.

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
08/12/09	1	Non-Heuweltjie	15:17	30.00	38.90
		Non-Heuweltjie	15:19	28.50	38.00
		Heuweltjie	15:21	27.90	43.20
		Heuweltjie	15:22	27.80	36.10
		Heuweltjie	15:24	27.50	34.10
		Heuweltjie	15:25	27.40	27.40
		Non-Heuweltjie	15:26	27.20	28.60
		Non-Heuweltjie	15:29	26.70	35.20
	2	Non-Heuweltjie	15:34	27.50	35.70
		Non-Heuweltjie	15:35	27.70	45.60
		Heuweltjie	15:37	27.70	34.80
		Heuweltjie	15:38	27.40	28.70
		Heuweltjie	15:40	27.20	36.60
		Heuweltjie	15:42	26.90	34.40
		Non-Heuweltjie	15:43	26.90	40.20
		Non-Heuweltjie	15:44	26.80	43.00
	3	Non-Heuweltjie	15:49	26.90	36.10
		Non-Heuweltjie	15:50	27.10	45.50
		Heuweltjie	15:52	27.10	39.70
		Heuweltjie	15:53	27.20	37.50
		Heuweltjie	15:54	27.30	50.30
		Heuweltjie	15:56	26.70	33.30
		Non-Heuweltjie	15:57	26.70	41.30
		Non-Heuweltjie	15:58	26.50	44.70
	4	Non-Heuweltjie	16:06	30.00	32.60
		Non-Heuweltjie	16:07	29.30	49.70
		Heuweltjie	16:09	28.70	55.60
		Heuweltjie	16:10	28.20	49.20
		Heuweltjie	16:11	27.90	43.40
		Heuweltjie	16:13	27.60	26.80
		Non-Heuweltjie	16:14	27.40	34.80
		Non-Heuweltjie	16:15	27.10	43.20

Appendix 3.1: Stomatal conductance readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
05/01/10	1	Non-Heuweltjie	13:56	40.5	51.8
		Non-Heuweltjie	13:55	41.4	64.6
		Heuweltjie	13:57	39.9	92.9
		Heuweltjie	13:58	39.4	78.8
		Heuweltjie	14:01	38.7	45.3
		Heuweltjie	14:02	38.4	89.5
		Non-Heuweltjie	14:03	38.2	56.8
		Non-Heuweltjie	14:04	38.3	59.7
	2	Non-Heuweltjie	14:13	38.2	72.6
		Non-Heuweltjie	14:11	38.2	31.3
		Heuweltjie	14:14	38	76.9
		Heuweltjie	14:15	37.8	88.7
		Heuweltjie	14:16	37.6	55.2
		Heuweltjie	14:17	37.7	82.1
		Non-Heuweltjie	14:18	37.6	69.6
		Non-Heuweltjie	14:20	37.5	52.3
	3	Non-Heuweltjie	14:25	38.1	70.1
		Non-Heuweltjie	14:24	38.4	83.3
		Heuweltjie	14:29	37.9	71.8
		Heuweltjie	14:30	37.8	93.4
		Heuweltjie	14:32	37.7	62
		Heuweltjie	14:35	37.4	62.8
		Non-Heuweltjie	14:37	37.5	74.3
		Non-Heuweltjie	14:39	37.4	74.3
	4	Non-Heuweltjie	14:45	38.1	59.5
		Non-Heuweltjie	14:44	38.2	45.6
		Heuweltjie	14:47	37.9	75.8
		Heuweltjie	14:48	37.8	90.4
		Heuweltjie	14:49	37.6	96.1
		Heuweltjie	14:50	37.3	72.6
		Non-Heuweltjie	14:51	37.3	72.5
		Non-Heuweltjie	14:55	37	70.3

Appendix 3.1: Stomatal conductance readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
02/02/10	1	Non-Heuweltjie	14:01	29.7	30.1
		Non-Heuweltjie	14:03	29	29.2
		Heuweltjie	14:04	12:00	29.9
		Heuweltjie	14:05	27.9	24.5
		Heuweltjie	14:07	27.5	22.3
		Heuweltjie	14:08	27.4	23.8
		Non-Heuweltjie	14:09	27.2	26
		Non-Heuweltjie	14:10	27.2	27.1
	2	Non-Heuweltjie	14:13	27.9	20.7
		Non-Heuweltjie	14:14	27.1	22.8
		Heuweltjie	14:15	27	14.8
		Heuweltjie	14:16	26.8	21.2
		Heuweltjie	14:16	26.6	21.5
		Heuweltjie	14:17	26.7	21.8
		Non-Heuweltjie	14:20	26.5	13.9
		Non-Heuweltjie	14:21	26.4	14.3
	3	Non-Heuweltjie	14:26	27	21
		Non-Heuweltjie	14:27	26.9	22.1
		Heuweltjie	14:28	26.7	17.1
		Heuweltjie	14:29	26.4	20.5
		Heuweltjie	14:30	26	21.7
		Heuweltjie	14:31	26.1	22.3
		Non-Heuweltjie	14:32	25.6	20.4
		Non-Heuweltjie	14:33	25.6	20.8
	4	Non-Heuweltjie	14:37	25.7	12
		Non-Heuweltjie	14:39	25.2	17
		Heuweltjie	14:41	24.7	17.6
		Heuweltjie	14:42	24.7	17.1
		Heuweltjie	14:43	24.4	19.4
		Heuweltjie	14:44	24.4	18.6
		Non-Heuweltjie	14:45	24.4	15
		Non-Heuweltjie	14:46	24.3	14.3

Appendix 3.1: Stomatal conductance readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
02/03/10	1	Non-Heuweltjie	14:38	41.9	37.5
		Non-Heuweltjie	14:40	40.8	53.5
		Heuweltjie	14:41	39.7	60.5
		Heuweltjie	14:42	38.7	74.8
		Heuweltjie	14:43	38	80.7
		Heuweltjie	14:44	37.3	67.2
		Non-Heuweltjie	14:45	36.7	44.9
		Non-Heuweltjie	14:46	36.3	43.1
	2	Non-Heuweltjie	14:51	36.6	31.3
		Non-Heuweltjie	14:52	36.4	64.5
		Heuweltjie	14:53	36	81.4
		Heuweltjie	14:55	35.9	68.7
		Heuweltjie	14:59	35.7	54.9
		Heuweltjie	15:00	35.7	60.4
		Non-Heuweltjie	15:01	35.6	49.1
		Non-Heuweltjie	15:02	35.6	44.8
	3	Non-Heuweltjie	15:04	36.4	44.9
		Non-Heuweltjie	15:05	36.4	34.1
		Heuweltjie	15:08	36.4	57.8
		Heuweltjie	15:09	35.7	51.3
		Heuweltjie	15:10	35.6	60.1
		Heuweltjie	15:11	35.5	59.9
		Non-Heuweltjie	15:13	35.4	44.5
		Non-Heuweltjie	15:14	35.4	41.2
	4	Non-Heuweltjie	15:17	36	45.2
		Non-Heuweltjie	15:18	36	48.9
		Heuweltjie	15:19	36	65.8
		Heuweltjie	15:20	35.9	61.3
		Heuweltjie	15:21	35.6	44.9
		Heuweltjie	15:22	35.6	53.7
		Non-Heuweltjie	15:23	35.5	68.8
		Non-Heuweltjie	15:24	35.6	34.1

Appendix 3.1: Stomatal conductance readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
08/04/10	1	Non-Heuweltjie	13:40	31.1	36.3
		Non-Heuweltjie	13:41	31	39.5
		Heuweltjie	13:42	30.7	32.6
		Heuweltjie	13:43	30.4	41
		Heuweltjie	13:44	30.1	39.9
		Heuweltjie	13:45	29.9	42.2
		Non-Heuweltjie	13:46	29.8	35.4
		Non-Heuweltjie	13:47	29.7	35.1
	2	Non-Heuweltjie	14:01	31.4	33.6
		Non-Heuweltjie	14:03	31.4	34.1
		Heuweltjie	14:04	31.3	42.1
		Heuweltjie	14:05	31.3	56.4
		Heuweltjie	14:06	31.3	40
		Heuweltjie	14:07	31.2	41.6
		Non-Heuweltjie	14:08	31.3	39.1
		Non-Heuweltjie	14:09	31.2	38.5
	3	Non-Heuweltjie	14:13	31.1	39.5
		Non-Heuweltjie	14:14	31.1	39.9
		Heuweltjie	14:15	31	44.2
		Heuweltjie	14:16	31	46.3
		Heuweltjie	14:17	31	40.1
		Heuweltjie	14:19	29.9	42.8
		Non-Heuweltjie	14:20	29.8	39.7
		Non-Heuweltjie	14:22	29.8	35.6
	4	Non-Heuweltjie	14:29	31.3	20.6
		Non-Heuweltjie	14:31	31.3	25.1
		Heuweltjie	14:32	31	38.6
		Heuweltjie	14:33	30.9	29.6
		Heuweltjie	14:34	30.9	24.9
		Heuweltjie	14:35	30.9	32.2
		Non-Heuweltjie	14:36	30.7	24.6
		Non-Heuweltjie	14:37	30.6	22.3

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area.

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
08/12/09	1	Non-Heuweltjie	-1.00	-22.00
		Non-Heuweltjie	-5.00	-13.50
		Heuweltjie	-5.00	-13.00
		Heuweltjie	-6.00	-14.00
		Heuweltjie	-4.50	-14.00
		Heuweltjie	-4.50	-15.00
		Non-Heuweltjie	-1.00	-23.00
		Non-Heuweltjie	-1.00	-14.00
	2	Non-Heuweltjie	-5.50	-15.50
		Non-Heuweltjie	-1.50	-10.50
		Heuweltjie	-1.50	-10.50
		Heuweltjie	-2.00	-18.50
		Heuweltjie	-0.50	-12.50
		Heuweltjie	-5.00	-6.50
		Non-Heuweltjie	-1.50	-30.00
		Non-Heuweltjie	-1.50	-14.00
	3	Non-Heuweltjie	-2.00	-12.00
		Non-Heuweltjie	-2.00	-9.00
		Heuweltjie	-1.50	-21.00
		Heuweltjie	-2.00	-10.50
		Heuweltjie	-2.00	-33.00
		Heuweltjie	-1.50	-16.00
		Non-Heuweltjie	-1.00	-10.50
		Non-Heuweltjie	-1.00	-14.00
	4	Non-Heuweltjie	-3.00	-14.00
		Non-Heuweltjie	-3.50	-21.00
		Heuweltjie	-2.00	-12.50
		Heuweltjie	-2.00	-20.00
		Heuweltjie	-3.00	-13.00
		Heuweltjie	-3.00	-14.00
		Non-Heuweltjie	-1.50	-9.00
		Non-Heuweltjie	-2.00	-12.00

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
06/01/10	1	Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-3.00	16.00
		Heuweltjie	-4.00	-18.00
		Heuweltjie	-4.00	17.50
		Heuweltjie	-5.00	-16.00
		Heuweltjie	-4.00	-16.00
		Non-Heuweltjie	-5.00	-20.00
		Non-Heuweltjie	-5.00	-18.50
	2	Non-Heuweltjie	-6.00	-20.00
		Non-Heuweltjie	-6.00	-19.00
		Heuweltjie	-4.00	-18.00
		Heuweltjie	-5.00	-18.00
		Heuweltjie	-5.00	-19.00
		Heuweltjie	-4.00	-19.00
		Non-Heuweltjie	-4.00	-24.50
		Non-Heuweltjie	-4.00	-20.00
	3	Non-Heuweltjie	-3.00	-17.00
		Non-Heuweltjie	-3.00	-17.00
		Heuweltjie	-2.00	-19.50
		Heuweltjie	-2.00	-15.50
		Heuweltjie	-3.00	-22.50
		Heuweltjie	-3.00	-15.00
		Non-Heuweltjie	-4.00	-19.00
		Non-Heuweltjie	-3.00	-18.50
	4	Non-Heuweltjie	-4.00	-16.00
		Non-Heuweltjie	-3.00	-15.00
		Heuweltjie	-2.00	-15.00
		Heuweltjie	-2.00	-14.00
		Heuweltjie	-3.00	-19.00
		Heuweltjie	-3.00	-14.00
		Non-Heuweltjie	-4.00	-18.00
		Non-Heuweltjie	-4.00	-20.50

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
02/02/10	1	Non-Heuweltjie	0.00	-16.50
		Non-Heuweltjie	0.00	-12.50
		Heuweltjie	0.00	-13.50
		Heuweltjie	0.00	-20.00
		Heuweltjie	0.00	-21.00
		Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-28.00
	2	Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-3.00	-19.00
		Heuweltjie	-2.50	-14.00
		Heuweltjie	-3.00	-15.00
		Heuweltjie	-2.50	-15.00
		Heuweltjie	-2.50	-17.00
		Non-Heuweltjie	-4.00	-17.00
		Non-Heuweltjie	-3.00	-18.00
	3	Non-Heuweltjie	-3.50	-20.00
		Non-Heuweltjie	-5.20	-19.00
		Heuweltjie	-3.50	-15.00
		Heuweltjie	-3.50	-14.00
		Heuweltjie	-3.50	-14.00
		Heuweltjie	-3.50	-14.00
		Non-Heuweltjie	-4.00	-19.00
		Non-Heuweltjie	-4.00	-20.00
	4	Non-Heuweltjie	-3.50	-18.00
		Non-Heuweltjie	-4.50	-18.00
		Heuweltjie	-3.00	-14.00
		Heuweltjie	-4.00	-16.00
		Heuweltjie	0.00	-12.00
		Heuweltjie	-2.50	-15.00
		Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-4.00	-18.00

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
02/02/10	1	Non-Heuweltjie	0.00	-16.50
		Non-Heuweltjie	0.00	-12.50
		Heuweltjie	0.00	-13.50
		Heuweltjie	0.00	-20.00
		Heuweltjie	0.00	-21.00
		Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-28.00
	2	Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-3.00	-19.00
		Heuweltjie	-2.50	-14.00
		Heuweltjie	-3.00	-15.00
		Heuweltjie	-2.50	-15.00
		Heuweltjie	-2.50	-17.00
		Non-Heuweltjie	-4.00	-17.00
		Non-Heuweltjie	-3.00	-18.00
	3	Non-Heuweltjie	-3.50	-20.00
		Non-Heuweltjie	-5.20	-19.00
		Heuweltjie	-3.50	-15.00
		Heuweltjie	-3.50	-14.00
		Heuweltjie	-3.50	-14.00
		Heuweltjie	-3.50	-14.00
		Non-Heuweltjie	-4.00	-19.00
		Non-Heuweltjie	-4.00	-20.00
	4	Non-Heuweltjie	-3.50	-18.00
		Non-Heuweltjie	-4.50	-18.00
		Heuweltjie	-3.00	-14.00
		Heuweltjie	-4.00	-16.00
		Heuweltjie	0.00	-12.00
		Heuweltjie	-2.50	-15.00
		Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-4.00	-18.00

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
02/03/10	1	Non-Heuweltjie	-3.00	-19.00
		Non-Heuweltjie	-2.00	-14.00
		Heuweltjie	-3.00	-21.00
		Heuweltjie	-3.00	-20.00
		Heuweltjie	-2.00	-29.00
		Heuweltjie	-2.50	-29.00
		Non-Heuweltjie	0.00	-21.00
		Non-Heuweltjie	-3.00	-15.00
	2	Non-Heuweltjie	-4.00	-18.00
		Non-Heuweltjie	0.00	-19.00
		Heuweltjie	0.00	-19.00
		Heuweltjie	-2.00	-20.00
		Heuweltjie	0.00	-20.00
		Heuweltjie	0.00	-18.00
		Non-Heuweltjie	0.00	-19.00
		Non-Heuweltjie	-2.00	-19.00
	3	Non-Heuweltjie	-2.00	-20.00
		Non-Heuweltjie	-2.00	-19.00
		Heuweltjie	-2.00	-25.00
		Heuweltjie	-3.00	-23.00
		Heuweltjie	-3.00	-22.00
		Heuweltjie	-3.00	-22.00
		Non-Heuweltjie	-4.00	-24.00
		Non-Heuweltjie	-4.00	-21.00
	4	Non-Heuweltjie	-3.00	-16.00
		Non-Heuweltjie	-2.00	-14.00
		Heuweltjie	0.00	-16.00
		Heuweltjie	0.00	-20.00
		Heuweltjie	-2.00	-17.00
		Heuweltjie	0.00	-19.00
		Non-Heuweltjie	-3.00	-20.00
		Non-Heuweltjie	0.00	-19.00

Appendix 3.2: Predawn and Midday leaf water potential readings taken over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
07/04/10	1	Non-Heuweltjie	-2.00	-20.00
		Non-Heuweltjie	-2.00	-19.00
		Heuweltjie	-2.00	-17.00
		Heuweltjie	-2.00	-16.00
		Heuweltjie	-2.00	-17.00
		Heuweltjie	0.00	-18.00
		Non-Heuweltjie	-2.00	-19.00
		Non-Heuweltjie	-2.00	-19.00
	2	Non-Heuweltjie	-2.00	-18.00
		Non-Heuweltjie	-2.00	-18.00
		Heuweltjie	0.00	-17.00
		Heuweltjie	0.00	-18.00
		Heuweltjie	-3.00	-19.00
		Heuweltjie	-3.00	-18.00
		Non-Heuweltjie	-2.00	-18.00
		Non-Heuweltjie	-3.00	-19.00
	3	Non-Heuweltjie	-4.00	-19.00
		Non-Heuweltjie	-2.00	-18.00
		Heuweltjie	-2.00	-18.00
		Heuweltjie	-3.00	-18.00
		Heuweltjie	-2.00	-19.00
		Heuweltjie	-2.00	-18.00
		Non-Heuweltjie	-2.00	-17.00
		Non-Heuweltjie	-3.00	-17.00
	4	Non-Heuweltjie	-4.00	-20.00
		Non-Heuweltjie	-2.00	-18.00
		Heuweltjie	-3.00	-19.00
		Heuweltjie	-3.00	-20.00
		Heuweltjie	-2.00	-19.00
		Heuweltjie	-2.00	-19.00
		Non-Heuweltjie	-4.00	-17.00
		Non-Heuweltjie	-3.00	-18.00

Appendix 3.3: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Stellenbosch study area.

Date	Heuweltjie	Description	Canopy density
08/12/09	1	Non-Heuweltjie	22
		Non-Heuweltjie	29
		Heuweltjie	97
		Heuweltjie	13
		Heuweltjie	10
		Heuweltjie	102
		Non-Heuweltjie	20
		Non-Heuweltjie	11
	2	Non-Heuweltjie	19
		Non-Heuweltjie	74
		Heuweltjie	23
		Heuweltjie	10
		Heuweltjie	6
		Heuweltjie	44
		Non-Heuweltjie	17
		Non-Heuweltjie	33
	3	Non-Heuweltjie	43
		Non-Heuweltjie	15
		Heuweltjie	25
		Heuweltjie	17
		Heuweltjie	43
		Heuweltjie	9
		Non-Heuweltjie	19
		Non-Heuweltjie	7
	4	Non-Heuweltjie	36
		Non-Heuweltjie	24
		Heuweltjie	16
		Heuweltjie	25
		Heuweltjie	32
		Heuweltjie	37
		Non-Heuweltjie	20
		Non-Heuweltjie	39

Appendix 3.3: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Canopy density
06/01/10	1	Non-Heuweltjie	31
		Non-Heuweltjie	40
		Heuweltjie	53
		Heuweltjie	70
		Heuweltjie	49
		Heuweltjie	40
		Non-Heuweltjie	33
		Non-Heuweltjie	39
	2	Non-Heuweltjie	30
		Non-Heuweltjie	42
		Heuweltjie	30
		Heuweltjie	33
		Heuweltjie	29
		Heuweltjie	41
		Non-Heuweltjie	28
		Non-Heuweltjie	39
	3	Non-Heuweltjie	51
		Non-Heuweltjie	27
		Heuweltjie	31
		Heuweltjie	22
		Heuweltjie	49
		Heuweltjie	21
		Non-Heuweltjie	33
		Non-Heuweltjie	28
	4	Non-Heuweltjie	43
		Non-Heuweltjie	36
		Heuweltjie	41
		Heuweltjie	40
		Heuweltjie	34
		Heuweltjie	52
		Non-Heuweltjie	33
		Non-Heuweltjie	42

Appendix 3.3: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Canopy density
02/02/10	1	Non-Heuweltjie	56
		Non-Heuweltjie	57
		Heuweltjie	35
		Heuweltjie	33
		Heuweltjie	23
		Heuweltjie	21
		Non-Heuweltjie	67
		Non-Heuweltjie	65
	2	Non-Heuweltjie	69
		Non-Heuweltjie	57
		Heuweltjie	26
		Heuweltjie	30
		Heuweltjie	31
		Heuweltjie	77
		Non-Heuweltjie	70
		Non-Heuweltjie	59
	3	Non-Heuweltjie	66
		Non-Heuweltjie	23
		Heuweltjie	26
		Heuweltjie	30
		Heuweltjie	36
		Heuweltjie	23
		Non-Heuweltjie	71
		Non-Heuweltjie	76
	4	Non-Heuweltjie	64
		Non-Heuweltjie	81
		Heuweltjie	33
		Heuweltjie	40
		Heuweltjie	37
		Heuweltjie	42
		Non-Heuweltjie	65
		Non-Heuweltjie	59

Appendix 3.3: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Canopy density
02/03/10	1	Non-Heuweltjie	78
		Non-Heuweltjie	84
		Heuweltjie	33
		Heuweltjie	31
		Heuweltjie	37
		Heuweltjie	28
		Non-Heuweltjie	79
		Non-Heuweltjie	78
	2	Non-Heuweltjie	87
		Non-Heuweltjie	79
		Heuweltjie	31
		Heuweltjie	25
		Heuweltjie	26
		Heuweltjie	30
		Non-Heuweltjie	66
		Non-Heuweltjie	85
	3	Non-Heuweltjie	78
		Non-Heuweltjie	88
		Heuweltjie	34
		Heuweltjie	30
		Heuweltjie	27
		Heuweltjie	24
		Non-Heuweltjie	87
		Non-Heuweltjie	88
	4	Non-Heuweltjie	75
		Non-Heuweltjie	69
		Heuweltjie	37
		Heuweltjie	33
		Heuweltjie	30
		Heuweltjie	32
		Non-Heuweltjie	78
		Non-Heuweltjie	86

Appendix 3.3: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Stellenbosch study area (continued).

Date	Heuweltjie	Description	Canopy density
08/04/10	1	Non-Heuweltjie	45
		Non-Heuweltjie	41
		Heuweltjie	6
		Heuweltjie	9
		Heuweltjie	13
		Heuweltjie	13
		Non-Heuweltjie	40
		Non-Heuweltjie	51
	2	Non-Heuweltjie	101
		Non-Heuweltjie	87
		Heuweltjie	8
		Heuweltjie	20
		Heuweltjie	14
		Heuweltjie	19
		Non-Heuweltjie	158
		Non-Heuweltjie	98
	3	Non-Heuweltjie	99
		Non-Heuweltjie	101
		Heuweltjie	19
		Heuweltjie	15
		Heuweltjie	10
		Heuweltjie	26
		Non-Heuweltjie	130
		Non-Heuweltjie	111
	4	Non-Heuweltjie	88
		Non-Heuweltjie	91
		Heuweltjie	19
		Heuweltjie	19
		Heuweltjie	23
		Heuweltjie	49
		Non-Heuweltjie	110
		Non-Heuweltjie	124

Appendix 3.4: Results from the test trial done on the pruning mass of the grapevines associated with the soils on and off the heuweltjies in the Stellenbosch study area.

Heuweltjie	Site	Vine	Main shoot mass (g)	Main shoot length (cm)	Nodia	Laterals	Lateral length (cm)	Nodia	Lateral Mass (g)
1	On	1	151.83	148	21	6	318	75	83.9
	On	2	98.8	121	18	5	310	81	96.4
	On	3	129.2	120	16	4	293	66	104.4
	On	4	109.6	112	17	3	178	33	73.5
	On	1	86.16	150	25	3	184	40	65.5
	Off	2	115	67.2	20	3	124	31	39.5
	Off	3	68.16	121	22	3	111.5	26	28
	Off	4	82	118	18	3	102	26	26.4
2	On	1	65	129	23	2	110	17	40.7
	On	2	255.2	229	33	9	216.3	150	216.3
	On	3	176.9	140	20	7	135	93	135
	On	4	143.1	176	30	7	114.5	95	114.5
	On	1	98.7	98.7	27	4	52.1	56	52.2
	Off	2	80	80	18	3	63.8	43	63.8
	Off	3	57.8	57.8	20	4	35.1	15	35
	Off	4	81.4	81.4	11	6	128	103	128
3	On	1	192.8	221.5	35	2	80	84	18.5
	On	2	113.1	125	24	6	348.5	70	101.8
	On	3	115.2	103.5	17	6	306	31	109.3
	On	4	105.5	157	32	3	134.5	51	37.7
	On	1	76	113.5	21	3	80.5	23	20.8
	Off	2	703.6	118	21	2	109	27	33.8
	Off	3	71.8	117	18	3	93.5	22	19.8
	Off	4	70.2	107	19	2	85.5	22	18.5
4	On	1	87.7	93	13	4	236.5	54	86.9
	On	2	144.4	157.5	20	3	124.5	31	26.7
	On	3	123.9	155	25	1	39.5	8	8.6
	On	4	154.7	138	20	4	156	37	36
	On	1	102.9	145	22	4	220	51	53.3
	Off	2	82.1	102	14	3	94.5	24	18
	Off	3	89.3	117.5	16	3	105.5	22	20.5
	Off	4	108.2	142	20	3	159	35	60

Appendix 3.5: Berry characteristics of grapes emanating from heuweltjie and non-heuweltjie sites in the Stellenbosch study area.

Heuweltjie	Site	Sugar content (Brix %)	Titratable acid (g/L)	pH
1	On	16.1	15.38	3.1
	Off	16.2	11.44	3.1
2	On	13.8	17.55	3
	Off	16.2	12.81	3
3	On	15.2	15.23	3
	Off	17	10.33	3.1
4	On	16.4	14.78	3
	Off	16.7	12.24	3

Appendix 3.6: Stomatal conductance readings taken over the three experimental months in the Robertson study area.

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
10/12/09	1	Non-Heuweltjie	17:07	27.7	23.2
		Non-Heuweltjie	17:08	27.6	27.6
		Heuweltjie	17:03	28.5	32.1
		Heuweltjie	17:03	28.2	21.9
		Heuweltjie	17:04	28	35.5
		Heuweltjie	17:05	28	36.3
		Non-Heuweltjie	16:58	28.7	33.9
		Non-Heuweltjie	16:57	29.1	34.7
	2	Non-Heuweltjie	16:37	31.5	28.9
		Non-Heuweltjie	16:40	37.1	12
		Heuweltjie	16:42	30.7	33.1
		Heuweltjie	16:44	30	23.2
		Heuweltjie	16:47	30.7	29.1
		Heuweltjie	16:49	29.2	35.1
		Non-Heuweltjie	16:50	29.1	32.7
		Non-Heuweltjie	16:52	25.7	29.2
	3	Non-Heuweltjie	16:21	37.1	45.6
		Non-Heuweltjie	16:22	36.1	46.5
		Heuweltjie	16:24	35.1	42.8

		Heuweltjie	16:26	34.3	48.4
		Heuweltjie	16:26	33.4	49.6
		Heuweltjie	16:27	32.5	54.3
		Non-Heuweltjie	16:29	31.5	32.4
		Non-Heuweltjie	16:30	30.7	25.3
	4	Non-Heuweltjie	15:32	35.2	36.5
		Non-Heuweltjie	15:48	33.5	41.3
		Heuweltjie	15:40	33.1	39.9
		Heuweltjie	15:41	33.1	31.4
		Heuweltjie	15:42	33.4	27.6
		Heuweltjie	15:43	33.4	28.2
		Non-Heuweltjie	15:44	33.4	31.3
		Non-Heuweltjie	15:46	33.3	31.1

Appendix 3.6: Stomatal conductance readings taken over the three experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
07/01/10	1	Non-Heuweltjie	14:06	32.10	32.60
		Non-Heuweltjie	14:07	32.20	32.50
		Heuweltjie	13:59	32.60	28.10
		Heuweltjie	14:00	32.40	32.90
		Heuweltjie	14:01	32.10	33.40
		Heuweltjie	14:04	32.20	31.10
		Non-Heuweltjie	13:57	33.00	33.60
		Non-Heuweltjie	13:55	33.90	29.10
	2	Non-Heuweltjie	14:12	33.60	35.60
		Non-Heuweltjie	14:14	33.10	36.00
		Heuweltjie	14:16	32.70	34.30
		Heuweltjie	14:18	32.60	40.30
		Heuweltjie	14:20	32.50	28.70
		Heuweltjie	14:21	32.50	33.80
		Non-Heuweltjie	14:24	32.60	37.50
		Non-Heuweltjie	14:26	32.40	38.10
	3	Non-Heuweltjie	14:31	32.70	44.90
		Non-Heuweltjie	14:35	32.50	28.10
		Heuweltjie	14:36	32.70	53.20

		Heuweltjie	14:38	33.00	45.50
		Heuweltjie	14:40	32.90	50.90
		Heuweltjie	14:42	32.30	49.80
		Non-Heuweltjie	14:43	32.40	41.90
		Non-Heuweltjie	14:46	32.20	35.40
	4	Non-Heuweltjie	14:49	33.90	45.00
		Non-Heuweltjie	14:51	33.70	42.10
		Heuweltjie	14:53	33.20	48.00
		Heuweltjie	14:56	33.00	21.90
		Heuweltjie	14:57	33.10	45.10
		Heuweltjie	14:58	33.30	46.20
		Non-Heuweltjie	15:00	33.40	26.80
		Non-Heuweltjie	15:01	33.30	57.40

Appendix 3.6: Stomatal conductance readings taken over the three experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Time	Leaf Temperature (°C)	Stomatal Conductance (mmol $m^2.s^{-1}$)
04/02/10	1	Non-Heuweltjie	14:04	34.70	64.20
		Non-Heuweltjie	14:05	34.50	75.60
		Heuweltjie	13:58	35.70	66.90
		Heuweltjie	14:00	35.40	40.50
		Heuweltjie	14:01	35.20	51.60
		Heuweltjie	14:02	35.10	67.30
		Non-Heuweltjie	14:09	34.00	44.10
		Non-Heuweltjie	14:10	34.10	39.00
	2	Non-Heuweltjie	14:13	34.80	48.60
		Non-Heuweltjie	14:15	34.60	58.50
		Heuweltjie	14:16	34.50	34.70
		Heuweltjie	14:19	34.50	53.40
		Heuweltjie	14:20	34.60	58.80
		Heuweltjie	14:21	34.50	41.30
		Non-Heuweltjie	14:23	34.60	60.40
		Non-Heuweltjie	14:24	35.00	70.10
	3	Non-Heuweltjie	14:30	35.80	63.60
		Non-Heuweltjie	14:32	35.40	68.10
		Heuweltjie	14:33	35.30	40.70

		Heuweltjie	14:35	34.80	58.10
		Heuweltjie	14:36	34.90	42.70
		Heuweltjie	14:37	34.90	57.90
		Non-Heuweltjie	14:39	34.80	52.00
		Non-Heuweltjie	14:41	34.60	60.20
	4	Non-Heuweltjie	14:45	36.10	54.30
		Non-Heuweltjie	14:46	35.30	62.70
		Heuweltjie	14:47	35.80	53.40
		Heuweltjie	14:48	35.50	47.40
		Heuweltjie	14:50	35.30	40.50
		Heuweltjie	14:51	35.20	50.50
		Non-Heuweltjie	14:52	35.10	50.80
		Non-Heuweltjie	14:53	35.20	57.90

Appendix 3.7: Predawn and Midday leaf water potential readings taken over the three experimental months in the Robertson study area.

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
12/12/09	1	Non-Heuweltjie	-2.50	-7.50
		Non-Heuweltjie	-1.50	-6.50
		Heuweltjie	-3.50	-1.50
		Heuweltjie	-4.50	-7.00
		Heuweltjie	-5.00	-10.00
		Heuweltjie	-4.00	-6.00
		Non-Heuweltjie	-2.00	-13.50
		Non-Heuweltjie	-2.00	-12.50
	2	Non-Heuweltjie	-3.00	-6.50
		Non-Heuweltjie	-2.50	-9.00
		Heuweltjie	-4.00	-16.00
		Heuweltjie	-3.50	-12.00
		Heuweltjie	-3.50	-16.00
		Heuweltjie	-3.00	-17.50
		Non-Heuweltjie	-2.50	-12.50
		Non-Heuweltjie	-2.50	-12.00
	3	Non-Heuweltjie	-3.50	-13.00
		Non-Heuweltjie	-2.50	-8.00
		Heuweltjie	-4.50	-12.50
		Heuweltjie	-3.50	-15.00

		Heuweltjie	-3.00	-8.00
		Heuweltjie	-3.00	-7.00
		Non-Heuweltjie	-2.00	-9.00
		Non-Heuweltjie	-2.50	-10.50
	4	Non-Heuweltjie	-3.00	-12.00
		Non-Heuweltjie	-3.50	-7.00
		Heuweltjie	-4.00	-9.50
		Heuweltjie	-4.00	-12.50
		Heuweltjie	-4.50	-11.00
		Heuweltjie	-5.00	-14.00
		Non-Heuweltjie	-3.50	-10.00
		Non-Heuweltjie	-3.00	-12.50

Appendix 3.8: Predawn and Midday leaf water potential readings taken over the three experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
07/01/10	1	Non-Heuweltjie	0.00	-18.00
		Non-Heuweltjie	0.00	-17.00
		Heuweltjie	0.00	-22.00
		Heuweltjie	0.00	-23.00
		Heuweltjie	0.00	-24.00
		Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-18.00
		Non-Heuweltjie	0.00	-21.50
	2	Non-Heuweltjie	0.00	-22.00
		Non-Heuweltjie	0.00	-20.00
		Heuweltjie	0.00	-26.00
		Heuweltjie	0.00	-25.00
		Heuweltjie	0.00	-25.50
		Heuweltjie	0.00	-27.00
		Non-Heuweltjie	0.00	-21.00
		Non-Heuweltjie	0.00	-22.00
	3	Non-Heuweltjie	0.00	-20.00
		Non-Heuweltjie	0.00	-24.00
		Heuweltjie	-2.00	-25.00
		Heuweltjie	0.00	-24.00

		Heuweltjie	0.00	-24.00
		Heuweltjie	0.00	-24.50
		Non-Heuweltjie	0.00	-24.00
		Non-Heuweltjie	0.00	-23.00
	4	Non-Heuweltjie	0.00	-19.00
		Non-Heuweltjie	0.00	-22.00
		Heuweltjie	0.00	-26.00
		Heuweltjie	0.00	-26.00
		Heuweltjie	-1.00	-23.00
		Heuweltjie	-2.00	-22.00
		Non-Heuweltjie	0.00	-18.00
		Non-Heuweltjie	2.00	-21.00

Appendix 3.8: Predawn and Midday leaf water potential readings taken over the three experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Predawn Water Potential	Midday Water Potential
05/02/10	1	Non-Heuweltjie	0.00	-20.00
		Non-Heuweltjie	0.00	-22.00
		Heuweltjie	0.00	-28.00
		Heuweltjie	0.00	-30.00
		Heuweltjie	0.00	-30.00
		Heuweltjie	0.00	-28.00
		Non-Heuweltjie	0.00	-24.00
		Non-Heuweltjie	0.00	-23.00
	2	Non-Heuweltjie	-4.00	-21.00
		Non-Heuweltjie	-3.50	-26.00
		Heuweltjie	-3.50	-26.00
		Heuweltjie	0.00	-27.00
		Heuweltjie	0.00	-30.00
		Heuweltjie	0.00	-29.00
		Non-Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-25.00
	3	Non-Heuweltjie	0.00	-22.00
		Non-Heuweltjie	0.00	-20.00
		Heuweltjie	-1.00	-32.00
		Heuweltjie	-2.00	-28.00

		Heuweltjie	-1.00	-29.00
		Heuweltjie	0.00	-28.00
		Non-Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-25.00
	4	Non-Heuweltjie	0.00	-18.00
		Non-Heuweltjie	0.00	-14.00
		Heuweltjie	0.00	-32.00
		Heuweltjie	0.00	-22.00
		Heuweltjie	0.00	-22.00
		Heuweltjie	0.00	-26.00
		Non-Heuweltjie	0.00	-9.00
		Non-Heuweltjie	0.00	-14.00

Appendix 3.9: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Robertson study area.

Date	Heuweltjie	Description	Canopy density
10/12/09	1	Non-Heuweltjie	15
		Non-Heuweltjie	21
		Heuweltjie	34
		Heuweltjie	19
		Heuweltjie	105
		Heuweltjie	28
		Non-Heuweltjie	14
		Non-Heuweltjie	15
	2	Non-Heuweltjie	21
		Non-Heuweltjie	22
		Heuweltjie	30
		Heuweltjie	36
		Heuweltjie	18
		Heuweltjie	20
		Non-Heuweltjie	11
		Non-Heuweltjie	31
	3	Non-Heuweltjie	25
		Non-Heuweltjie	27
		Heuweltjie	48

		Heuweltjie	47
		Heuweltjie	24
		Heuweltjie	44
		Non-Heuweltjie	33
		Non-Heuweltjie	23
	4	Non-Heuweltjie	33
		Non-Heuweltjie	68
		Heuweltjie	24
		Heuweltjie	35
		Heuweltjie	56
		Heuweltjie	49
		Non-Heuweltjie	25
		Non-Heuweltjie	43

Appendix 3.9: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Canopy density
07/01/10	1	Non-Heuweltjie	23
		Non-Heuweltjie	42
		Heuweltjie	56
		Heuweltjie	65
		Heuweltjie	47
		Heuweltjie	77
		Non-Heuweltjie	24
		Non-Heuweltjie	21
	2	Non-Heuweltjie	29
		Non-Heuweltjie	35
		Heuweltjie	67
		Heuweltjie	56
		Heuweltjie	87
		Heuweltjie	44
		Non-Heuweltjie	33
		Non-Heuweltjie	28
	3	Non-Heuweltjie	36
		Non-Heuweltjie	21
		Heuweltjie	55

		Heuweltjie	54
		Heuweltjie	47
		Heuweltjie	41
		Non-Heuweltjie	26
		Non-Heuweltjie	34
	4	Non-Heuweltjie	32
		Non-Heuweltjie	23
		Heuweltjie	58
		Heuweltjie	66
		Heuweltjie	59
		Heuweltjie	44
		Non-Heuweltjie	39
		Non-Heuweltjie	35

Appendix 3.9: Canopy density readings as measured taken with the ceptometer over the five experimental months in the Robertson study area (continued).

Date	Heuweltjie	Description	Canopy density
04/02/10	1	Non-Heuweltjie	27
		Non-Heuweltjie	30
		Heuweltjie	45
		Heuweltjie	77
		Heuweltjie	65
		Heuweltjie	68
		Non-Heuweltjie	30
		Non-Heuweltjie	26
	2	Non-Heuweltjie	24
		Non-Heuweltjie	36
		Heuweltjie	70
		Heuweltjie	67
		Heuweltjie	74
		Heuweltjie	59
		Non-Heuweltjie	28
		Non-Heuweltjie	23
	3	Non-Heuweltjie	22
		Non-Heuweltjie	29
		Heuweltjie	67

		Heuweltjie	55
		Heuweltjie	67
		Heuweltjie	78
		Non-Heuweltjie	31
		Non-Heuweltjie	30
	4	Non-Heuweltjie	24
		Non-Heuweltjie	35
		Heuweltjie	64
		Heuweltjie	70
		Heuweltjie	76
		Heuweltjie	77
		Non-Heuweltjie	29
		Non-Heuweltjie	25

Appendix 3.10: Results from the test trial done on the pruning mass of the grapevines associated with the soils on and off the heuweltjies in the Robertson study area.

Heuweltjie	Site	Vine	Main shoot mass (g)	Main shoot length (cm)	Nodia	Laterals	Lateral length (cm)	Nodia	Lateral Mass (g)
1	On	1	76.7	127	18	3	149	25	35.5
	On	2	90.5	155	24	3	102	16	29
	On	3	89.9	156	19	2	64	13	10.1
	On	4	109.4	172	25	2	109.5	21	23.8
	Off	1	89.7	135	23	3	245	50	56.7
	Off	2	274.2	497	46	4	133	29	30.4
	Off	3	99.3	195	27	2	119	30	16
	Off	4	67.1	138	22	2	150	32	22
2	On	1	105	127	12	4	311	40	54.5
	On	2	80.1	105	10	2	154	18	20.1
	On	3	75.3	119	10	2	80	12	11.2
	On	4	77.6	105	11	2	65	10	11.3
	Off	1	121.5	265	19	4	254	59	31.5
	Off	2	94.1	155	15	2	120	19	22.1
	Off	3	97	206	29	2	141.5	36	24.5
	Off	4	65.7	137	21	2	60	18	10.6
3	On	1	92.4	147	22	3	90.4	16	30.8
	On	2	96.8	150	23	2	69	13	25.9
	On	3	86	146	22	2	70	14	28

	On	4	101	161	25	3	81.3	17	40.9
	Off	1	224.16	255	25	2	155	35	42
	Off	2	132.8	240.9	41	4	162.8	33	40.8
	Off	3	169.5	265.4	48	3	159.3	35	39.7
	Off	4	200.4	251.4	50	4	171.2	41	42.9
4	On	1	122.1	313	29	1	39	12	43
	On	2	79.53	135	20	5	157	43	19.1
	On	3	61.2	179	29	2	87	24	7.9
	On	4	94.3	150	19	2	114	24	16.5
	Off	1	158.3	217	26	4	162	36	36.2
	Off	2	104.2	181	32	2	120	39	17
	Off	3	99	143	38	1	72	15	9.1
	Off	4	80.4	248	40	2	70	14	10.9

Appendix 3.11: Berry characteristics of grapes emanating from heuweltjie and non-heuweltjie sites in the Robertson study area.

Heuweltjie	**Site**	**Sugar content (Brix %)**	**Titratable acid (g/L)**	**pH**
1	On	20.2	7.94	3.33
	Off	19.2	7.77	3.28
2	On	18.4	7.23	3.26
	Off	18.7	6.95	3.49
3	On	16.4	7.59	3.26
	Off	16.3	8.19	3.27
4	On	17.3	7.23	3.35
	Off	16.2	8.38	3.27

Appendix 4.1: Weather data of the Stellenbosch study area as obtained from Alto weather station (Averages from 1998 to 2008 are included).

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	ET0 (mm)	RH (%)
2009	January	27.23 (28.49)	16.15 (16.57)	7.37 (12.91)	5.11	60.88
	February	30.15 (29.3)	17.81 (16.97)	24.38 (20.34)	5.15	54.36
	March	28.81 (27.26)	16.22 (15.67)	3.3 (28.81)	4.02	57.44
	April	25.65 (24.37)	15.05 (14.23)	45.21 (53.45)	2.57	59.48
	May	20.17 (20.47)	12.3 (12.63)	109.73 (105.01)	1.52	69.87
	June	17.96 (18.37)	11.71 (11.19)	118.11 (117.14)	1.48	72.99
	July	19.12 (18.37)	11.31 (10.29)	129.54 (101.65)	2.02	60.38
	August	18.36 (17.28)	10.15 (9.9)	76.96 (99.04)	2.13	67.33
	September	18.14 (19.48)	10.45 (10.54)	103.12 (67.45)	2.47	71.05
	October	23.2 (22.9)	12.85 (12.37)	67.82 (53.33)	4.04	61.32
	November	23.57 (23.99)	13.81 (13.64)	110.49 (58.3)	4.42	61.53
	December	26.06 (26.56)	14.84 (15.42)	3.56 (31.5)	5.05	58.76
2010	January	28.78	16.47	1.52	5.55	58.86
	February	29.37	16.98	34.54	4.77	60.25
	March	29.24	17.37	8.89	4.26	57.86
	April	24.27	13.80	24.13	2.89	59.87

Appendix 4.2: Weather data of the Robertson study area, as obtained from the weather station situated on the farm.

Year	Month	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	ET0 (mm)	RH (%)
2009	January	32.92	15.76	1.4	1.19	29.84
	February	33.90	16.36	6	1.21	29.50
	March	32.46	14.79	9.8	1.18	30.23
	April	28.01	12.70	28.2	1.12	38.87
	May	23.26	8.81	30.6	1.04	42.26
	June	19.56	7.11	21.2	0.98	49.03
	July	20.25	4.98	35.4	0.96	43.65
	August	21.39	5.72	15.4	0.98	38.35
	September	22.22	8.57	9.4	1.02	34.97
	October	27.15	11.10	23.6	1.10	34.39
	November	29.14	12.67	23.4	1.13	31.00
	December	31.55	13.76	3	1.17	27.35
2010	January	34.72	16.33	2.20	1.21	25.39
	February	32.94	16.27	43.80	1.20	31.57
	March	31.51	15.51	8.20	1.18	35.39
	April	27.73	10.72	4.20	1.10	35.17